ENGINEERING EDUCATION

ESSAYS FOR ENGLISH

SELECTED AND EDITED

BY

RAY PALMER BAKER, Ph.D.

Professor of English and Head of the Department of Arts, Science, and Business Administration
Rensselaer Polytechnic Institute

NEW YORK

JOHN WILEY & SONS, Inc.

LONDON: CHAPMAN & HALL, LIMITED

PREFACE TO THE FIRST EDITION

ALTHOUGH I can thank individually the authors and publishers whose generosity has made this collection possible, I can mention only a few of those who have contributed to it less directly. Of my colleagues in pure and applied science, Dr. A. T. Lincoln and Dr. M. A. Hunter have been notably helpful. Dr. Arthur L. Eno, of the Department of English, has criticized the manuscript from a literary point of view. To Miss Harriet R. Peck, Librarian of the Institute, who has made available the growing literature on the problems of engineering education, I am especially indebted.

R. P. B.

Troy, New York
January 2, 1919

INTRODUCTION TO THE FIRST EDITION

As instructors in English will see by a glance at the table of contents, this volume has been planned for students of engineering.

The avenues which it opens to those who are dealing with the fundamental processes of exposition are so evident that reference to them would be impertinent. It may not be out of place, however, to direct attention toward three features of the text that are largely original; in character, authoritativeness, and arrangement, it represents distinct departures from time-honored methods of selection.

The articles, written within the last decade, are of immediate interest. Although students ought to be familiar with the earlier phases of the debate between the champions of utility and culture in education, and with the methods of such formidable antagonists as Huxley and Arnold, the specific issues over which they clashed are apparently settled, and not unnaturally are regarded by freshmen and sophomores as remote and unimportant. Other issues have since arisen. One of the most valuable features of this volume is its indication that experience and authority point toward a decision that few

undergraduates expect. As a result, it stimulates, in a novel manner, the clash of opinion which is the strongest incentive to thought.

In another way, also, the collection is unique; for in no instance are the writers professional men of letters. In every case they may claim for their views the sanction of success—even distinction—in pure or applied science. Consequently their observations are certain to appeal to undergraduates—hero-worshippers at heart—who are inclined to test experience by deeds instead of books. What the Chief Critic of the Nineteenth Century says regarding the classics means little to freshmen or sophomores who find their highest delight in the antennæ of a wireless station; what the Consulting Engineer to the General Electric Company says regarding them means much.

Moreover, the arrangement of the articles—recent and authoritative as they are—is such that they present an ideal of engineering education that cannot be found elsewhere. Every student will be attracted by the goal toward which the argument moves.

What these three departures mean to instructors in English cannot be exaggerated. They mean that students will be eager to think and to express their ideas as effectively as possible; that they will come to accept a point of view with which they may have had little sympathy in the past; that they will be able to regard the process of education as a whole, and so fit into their proper niches the ele-

ments essential to success. With the place of language and literature thus established, they will approach them with renewed zest and determination.

Since the volume will be used chiefly in elementary courses in exposition, where accuracy is essential, the text has been prepared with particular care. In one instance the author's revised copy has been selected for publication. Another essay is a composite drawn from two different sources. As several articles are based on reports which were never submitted for verification, errors in the originals are not uncommon. These mistakes have been corrected. Where parallel passages occur, the most acceptable readings have been retained. Moreover, to avoid confusion on the part of students, usage has been standardized wherever possible. To adapt the volume to their needs, and to keep it within reasonable bounds, all the articles except those by Professor Ranum and Professor Hunter have been materially abridged. Although much has thus been omitted, nothing except a few connectives has been added; and the thought remains essentially the same.

CONTENTS

PHYSICS

CHEMISTRY

IMAGINATION AND INVENTION

THE ORIGINS OF ENGINEERING EDUCATION

I

EVOLUTION OF THE SCIENTIFIC INVESTIGATOR

SIMON NEWCOMB

[FEW men have been better qualified than Simon Newcomb (1835–1909) to interpret the aims of science. No other American at any rate has achieved such distinction in research and written with such lucidity regarding his achievements. So various were Newcomb's interests, and so numerous are his books and articles, that only the most significant can be considered here. Educated at his father's school in Nova Scotia, and at Harvard University, he soon found that his interests lay in mathematics and astronomy; and in due time he became Senior Professor in the Navy of the United States and Professor of Mathematics at the Johns Hopkins University. Of his success in investigation the best criteria are the honors conferred upon him in recognition of his discoveries: degrees in many of the greatest universities; decorations by foreign governments; medals by various associations, and positions of trust in the learned societies of America. He was, for instance, the first native American after Franklin to be elected an associate of the Institute of France. Among medals which he received were the Gold Medal of the Royal Astronomical Society and the Copley Medal of the Royal Society. At different times he was president of the American Association for the Advancement of Science, the Society for Physical Research, the Astronomical and Astrophysical Society of America, and the American Mathematical Society. While President of the International

Congress of Arts and Sciences, in 1904, he delivered the following address, which is abridged, by permission of the Smithsonian Institution, from the *Report* for 1904. In addition to articles demanded by his editorship of the *American Journal of Mathematics* and the *Nautical Almanac,* he is the author of three hundred monographs on mathematical and astronomical subjects. Most of these are to be found in the *Astronomical Papers.* Many others, more popular in treatment, have been made easily accessible, and have done much to stimulate interest in natural phenomena. Nor did Newcomb forget the world of Man in the world of Nature. In several books he set forth his theories of economics, and in a novel and a volume of reminiscences he epitomized what he had learned of society. Few writers have been better qualified to trace the progress of science from the dawn of civilization to the end of the nineteenth century.]

THE movement which culminated in making the nineteenth century ever memorable in history is the outcome of a long series of causes, acting through many centuries, which are worthy of special attention on such an occasion as this. In setting them forth we should avoid laying stress on those visible manifestations which, striking the eye of every beholder, are in no danger of being overlooked, and search rather for those agencies which are liable to be blotted out by the very brilliancy of the results to which they have given rise.

Our inquiry into the logical order of the causes which have made our civilization what it is to-day will be facilitated by bringing to mind certain elementary considerations—ideas so familiar that setting them forth may seem like citing a body of truisms—and yet so frequently overlooked, not only individually, but in their relation to each other,

that the conclusion to which they lead may be lost to sight. One of these propositions is that psychical rather than material causes are those which we should regard as fundamental in directing the development of the social organism. The human intellect is the really active agent in every branch of endeavor—the *primum mobile* of civilization—and all those material manifestations to which our attention is so often directed are to be regarded as secondary to this first agency. If it be true that "in the world is nothing great but man; in man is nothing great but mind," then should the keynote of our discourse be the recognition of this first and greatest of powers.

Another well-known fact is that those applications of the forces of Nature to the promotion of human welfare which have made our age what it is are of such comparatively recent origin that we need go back only a single century to antedate their most important features, and scarcely more than four centuries to find their beginning. It follows that the subject of our inquiry should be the commencement, not many centuries ago, of a new form of intellectual activity.

With this point of view in mind, our next inquiry should be into the nature of that activity and its relation to the stages of progress which preceded and followed its beginning. The superficial observer, who sees the oak but forgets the acorn, may tell us that the special qualities which have brought out such great results are expert scientific knowledge

Congress of Arts and Sciences, in 1904, he delivered the following address, which is abridged, by permission of the Smithsonian Institution, from the *Report* for 1904. In addition to articles demanded by his editorship of the *American Journal of Mathematics* and the *Nautical Almanac,* he is the author of three hundred monographs on mathematical and astronomical subjects. Most of these are to be found in the *Astronomical Papers.* Many others, more popular in treatment, have been made easily accessible, and have done much to stimulate interest in natural phenomena. Nor did Newcomb forget the world of Man in the world of Nature. In several books he set forth his theories of economics, and in a novel and a volume of reminiscences he epitomized what he had learned of society. Few writers have been better qualified to trace the progress of science from the dawn of civilization to the end of the nineteenth century.]

THE movement which culminated in making the nineteenth century ever memorable in history is the outcome of a long series of causes, acting through many centuries, which are worthy of special attention on such an occasion as this. In setting them forth we should avoid laying stress on those visible manifestations which, striking the eye of every beholder, are in no danger of being overlooked, and search rather for those agencies which are liable to be blotted out by the very brilliancy of the results to which they have given rise.

Our inquiry into the logical order of the causes which have made our civilization what it is to-day will be facilitated by bringing to mind certain elementary considerations—ideas so familiar that setting them forth may seem like citing a body of truisms—and yet so frequently overlooked, not only individually, but in their relation to each other,

that the conclusion to which they lead may be lost to sight. One of these propositions is that psychical rather than material causes are those which we should regard as fundamental in directing the development of the social organism. The human intellect is the really active agent in every branch of endeavor—the *primum mobile* of civilization—and all those material manifestations to which our attention is so often directed are to be regarded as secondary to this first agency. If it be true that "in the world is nothing great but man; in man is nothing great but mind," then should the keynote of our discourse be the recognition of this first and greatest of powers.

Another well-known fact is that those applications of the forces of Nature to the promotion of human welfare which have made our age what it is are of such comparatively recent origin that we need go back only a single century to antedate their most important features, and scarcely more than four centuries to find their beginning. It follows that the subject of our inquiry should be the commencement, not many centuries ago, of a new form of intellectual activity.

With this point of view in mind, our next inquiry should be into the nature of that activity and its relation to the stages of progress which preceded and followed its beginning. The superficial observer, who sees the oak but forgets the acorn, may tell us that the special qualities which have brought out such great results are expert scientific knowledge

and rare ingenuity, directed to the application of the powers of steam and electricity. From this point of view the great inventors and the great captains of industry were the first agents in bringing about the modern era. But the more careful inquirer will see that the work of these men was possible only through a knowledge of the laws of Nature which had been gained by men whose work took precedence of theirs in logical order, and that success in invention has been measured by the completeness of such knowledge. While giving all due honor to the great inventors, let us remember that the first place is that of the great investigators, whose forceful intellects opened the way to secrets previously hidden from men. Let it be an honor and not a reproach to these men that they were not actuated by the love of gain, and did not keep utilitarian ends in view in the pursuit of their researches. If it seems that in neglecting such ends they were leaving undone the most important part of their work, let us remember that Nature turns a forbidding face to those who pay her court with the hope of gain, and is responsive only to those suitors whose love for her is pure and undefiled. The true man of science has no such expression in his vocabulary as "useful knowledge." His domain is as wide as Nature itself, and he best fulfills his mission when he leaves to others the task of applying the knowledge he gives to the world.

From this point of view it is clear that the primary agent in the movement which has elevated man to

the masterful position he now occupies is the scientific investigator. He it is whose work has deprived plague and pestilence of their terrors, alleviated human suffering, girdled the earth with the electric wire, bound the continent with the iron way, and made neighbors of the most distant nations. As the first agent which has made possible this meeting of his representatives, let his evolution be this day our worthy theme. As we follow the evolution of an organism by studying the stages of its growth, so we have to show how the work of the scientific investigator is related to the ineffectual efforts of his predecessors.

In our time we think of the process of development in Nature as one going continuously forward through the combination of the opposite processes of evolution and dissolution. The tendency of our thought has been in the direction of banishing cataclysms to the theological limbo, and viewing Nature as a sleepless plodder, endowed with infinite patience, waiting through long ages for results. I do not contest the truth of the principle of continuity on which this view is based. But it fails to make known to us the whole truth. The building of a ship from the time that her keel is laid until she is making her way across the ocean is a slow and gradual progress; yet there is a cataclysmic epoch opening up a new era in her history. It is the moment when, after lying for months or years a dead, inert, immovable mass, she is suddenly endowed with the power of motion and, as if imbued with life, glides into the

stream, eager to begin the career for which she was designed.

I think it is thus in the development of humanity. Long ages may pass during which a race, to all external observation, appears to be making no real progress. Additions may be made to learning, and the records of history may constantly grow; but there is nothing in its sphere of thought or in the features of its life that can be called essentially new. Yet Nature may have been all along slowly working in a way which evades our scrutiny until the result of her operations suddenly appears in a new and revolutionary movement, carrying the race to a higher plane of civilization.

It is not difficult to point out such epochs in human progress. The greatest of all, because it was the first, is one of which we find no record either in written or geological history. It was the epoch when our progenitors first took conscious thought of the morrow, first used the crude weapons which Nature had placed within their reach to kill their prey, first built a fire to warm their bodies and cook their food. I love to fancy that there was some one first man, the Adam of evolution, who did all this, and who used the power thus acquired to show his fellows how they might profit by his example. When the members of the tribe or community which he gathered around him began to conceive of life as a whole —to include yesterday, to-day, and to-morrow in the same mental grasp—to think how they might

apply the gifts of Nature to their own uses, a movement was begun which ultimately lead to civilization.

Long indeed must have been the ages required for the development of this rudest primitive community into the civilization revealed to us by the most ancient tablets of Egypt and Assyria. After spoken language was developed, and after the rude representation of ideas by visible marks drawn to resemble them had long been practiced, some Cadmus must have invented an alphabet. When the use of written language was thus introduced, the word of command ceased to be confined to the range of the human voice, and it became possible for master minds to extend their influence as far as a written message could be carried. Then were communities gathered into provinces, provinces into kingdoms, kingdoms into the great empires of antiquity. Then arose a stage of civilization which we find pictured in the most ancient records—a stage in which men were governed by laws that were perhaps as wisely adapted to their conditions as our laws are to ours—in which the phenomena of Nature were rudely observed and striking occurrences in the earth or in the heavens recorded in the annals of the nation.

Vast was the progress of knowledge during the interval between these empires and the century in which modern science began. Yet, if I am right in making a distinction between the slow and regular steps of progress, each growing naturally out of that

which preceded it, and the entrance of the mind at some fairly definite epoch into an entirely new sphere of activity, it would appear that there was only one such epoch during the entire interval. This was when abstract geometrical reasoning commenced, and astronomical observations aiming at precision were recorded, compared, and discussed. Closely associated with it must have been the construction of the forms of logic. The radical difference between the demonstration of a theorem of geometry and the reasoning of everyday life which the masses of men must have practiced from the beginning, and which few even to-day ever get beyond, is so evident at a glance that I need not dwell upon it. The principal feature of this advance is that, by one of those antinomies of the human intellect of which examples are not wanting even in our time, the development of abstract ideas preceded the concrete knowledge of natural phenomena. When we reflect that in the geometry of Euclid the science of space was brought to such logical perfection that even to-day its teachers are not agreed as to the practicability of any great improvement upon it, we cannot avoid the feeling that a very slight change in the direction of the intellectual activity of the Greeks would have led to the beginning of natural science. But it seems that the very purity and perfection which were aimed at in their system of geometry stood in the way of any extension or application of its methods and spirit to the field of Nature. One example is worthy of atten-

tion. In modern teaching the idea of magnitude as generated by motion is freely introduced. A line is described by a moving point; a plane, by a moving line; a solid, by a moving plane. It may, at first sight, seem singular that this conception finds no place in the Euclidean system. But we may regard the omission as a mark of logical purity and rigor. Had the real or supposed advantages of introducing motion into geometrical conceptions been suggested to Euclid, we may suppose him to have replied that the theorems of space are independent of time; that the idea of motion necessarily implies time, and that, in consequence, to avail ourselves of it would be to introduce an extraneous element into geometry.

It is possible that the contempt of the ancient philosophers for the practical application of their science, which has continued in some form to our own time, and which is not altogether unwholesome, was a powerful factor in the same direction. The result was that, in keeping geometry pure from ideas which do not belong to it, it failed to form what might otherwise have been the basis of physical science. Its founders missed the discovery that methods similar to those of geometric demonstration can be extended into other and wider fields than that of space. Thus, not only the development of applied geometry, but the reduction of other conceptions to a rigorous mathematical form, was indefinitely postponed.

Astronomy is necessarily a science of observation

pure and simple, in which experiment can have no place except as an auxiliary. The vague accounts of striking celestial phenomena handed down by the priests and astrologers of antiquity were followed in the time of the Greeks by observations having, in form at least, a rude approach to precision, though nothing like the degree of precision that the astronomer of to-day would reach with the naked eye, aided by such instruments as he could fashion from the tools at the command of the ancients.

The rude observations commenced by the Babylonians were continued with gradually improving instruments—first by the Greeks and afterward by the Arabs—but the results failed to afford any insight into the true relation of the earth to the heavens. What was most remarkable in this failure is that, to take a first step which would have led on to success, no more was necessary than a course of abstract thinking vastly easier than that required for working out the problems of geometry. That space is infinite is an unexpressed axiom tacitly assumed by Euclid and his successors. If this were combined with the most elementary consideration of the properties of the triangle, it would be seen that a body of any given size could be placed at such a distance in space as to appear to us like a point. Hence, a body as large as our earth, which was known to be a globe from the time that the ancient Phœnicians navigated the Mediterranean, if placed in the heavens at a sufficient distance, would look like a star. The obvious conclusion that the stars might be

bodies like our globe, shining either by their own light or by that of the sun, would have been a first step to the understanding of the true system of the world.

There is historical evidence that this deduction did not wholly escape the Greek thinkers. It is true that the critical student will assign little weight to the current belief that the vague theory of Pythagoras—that fire is at the center of all things—implies a conception of the heliocentric theory of the solar system. But the testimony of Archimedes, confused though it is in form, leaves no serious doubt that Aristarchus of Samos not only propounded the view that the earth revolves both on its own axis and around the sun, but that he correctly removed the great stumbling-block in the way of this theory by adding that the distance of the fixed stars was infinitely greater than the dimensions of the earth's orbit. Even the world of philosophy was not yet ready for this conception, and, so far from seeing the reasonableness of the explanation, we find Ptolemy arguing against the rotation of the earth on grounds which careful observations of the phenomena around him would have shown to be ill-founded.

Physical science, if we may apply that term to an uncoördinated body of facts, was successfully cultivated from the earliest times. Something must have been known of the properties of metals, and the art of extracting them from their ores must have been practiced from the time that coins and medals were first stamped. The properties of the most

common compounds were discovered by alchemists in their vain search for the philosopher's stone, but no actual progress worthy of the name rewarded the practitioners of the black art.

Perhaps the first approach to a correct method was that of Archimedes, who, by much thinking, worked out the law of the lever, reached the conception of the center of gravity, and demonstrated the first principles of hydrostatics. It is remarkable that he did not extend his researches into the phenomena of motion, whether spontaneous or produced by force. The stationary condition of the human intellect is most strikingly illustrated by the fact that not until the time of Leonardo da Vinci was any substantial advance made on his discovery. To sum up in one sentence the most characteristic feature of ancient and mediæval science, we see a notable contrast between the precision of thought implied in the construction and demonstration of geometrical theorems and the vague indefinite character of the ideas of natural phenomena, a contrast which did not disappear until the foundations of modern science began to be laid.

We should miss the most essential point of the difference between mediæval and modern learning if we looked upon it as mainly a difference either in the precision or the amount of knowledge. The development of both of these qualities would, under any circumstances, have been slow and gradual, but sure. We can hardly suppose that any one genera-

tion, or even any one century, would have seen the complete substitution of exact for inexact ideas. Slowness of growth is as inevitable in the case of knowledge as in that of a growing organism. The most essential point of difference is one of those seemingly slight ones the importance of which we are too apt to overlook. It was like the drop of blood in the wrong place, which someone has told us makes all the difference between a philosopher and a maniac. It was all the difference between a living tree and a dead one, between an inert mass and a growing organism. The transition of knowledge from the dead to the living form must, in any complete review of the subject, be looked upon as the really great event of modern times. Before this event the intellect was bound down by a scholasticism which regarded knowledge as a rounded whole, the parts of which were written in books and carried in the minds of learned men. The student was taught from the beginning of his work to look upon authority as the foundation of his beliefs. The older the authority, the greater the weight it carried. So effective was this teaching that it seems never to have occurred to individual men that they had all the opportunities of discovering truth ever enjoyed by Aristotle, with the added advantage of all his knowledge to begin with. Advanced as was the development of formal logic, the practical logic was wanting which could see that the last of a series of authorities, every one of which rested on those which pre-

ceded it, could never form a surer foundation for any doctrine than that supplied by its original propounder.

The result of this view of knowledge was that, although during the fifteen centuries following the death of the geometer of Syracuse great universities were founded at which generations of professors expounded all the learning of their time, neither professor nor student ever suspected what latent possibilities for good were concealed in the most familiar operations of Nature. Everyone felt the wind blow, saw water boil, and heard the thunder crash, but never thought of investigating the forces at play. Up to the middle of the fifteenth century, the most acute observer could scarcely have seen the dawn of a new era.

In view of this state of things, it must be regarded as one of the most remarkable facts in history that four or five men, whose mental constitution was either typical of the new order of things, or who were powerful agents in bringing it about, were all born during the fifteenth century, four of them at least at so nearly the same time as to be contemporaries.

Leonardo da Vinci, whose artistic genius has charmed succeeding generations, was also the first practical engineer of his time, and the first man after Archimedes to make a substantial advance in developing the laws of motion. That the world was not prepared to make use of his scientific discoveries

does not detract from the significance which must attach to the period of his birth.

Shortly after him was born the great navigator whose bold spirit was to make known a new world, thus giving to commercial enterprise that impetus which was so powerful an agent in bringing about a revolution in the thoughts of men.

The birth of Columbus was soon followed by that of Copernicus, the first after Aristarchus to demonstrate the true system of the world. In him more than in any of his contemporaries do we see the struggle between the old forms of thought and the new. It seems almost pathetic, and is certainly most suggestive of the general view of knowledge taken at this time that, instead of claiming credit for bringing to light great truths before unknown, he made a labored attempt to show that after all there was nothing really new in his system, which he claimed to date from Pythagoras and Philolaus. In this connection it is curious that he makes no mention of Aristarchus, who, I think, will be regarded by conservative historians as his only demonstrated predecessor. To the hold of the older ideas upon his mind we must attribute the fact that in constructing his system he took great pains to make as little change as possible in ancient conceptions.

Luther, the greatest thought-stirrer of them all, practically of the same generation with Copernicus, Leonardo, and Columbus, does not come in as a scientific investigator but as the great loosener of

chains which had so fettered the intellect of men that they dared not think otherwise than as the authorities thought.

Almost coeval with the advent of these intellects was the invention of printing with movable type. Gutenberg was born during the first decade of the century, and his associates and others credited with the invention not many years afterward. If we accept the principle on which I am basing my argument, that we should assign the first place to the birth of those psychic agencies which started men on new lines of thought, then surely was the fifteenth the wonderful century.

Let us not forget that, in assigning the actors then born to their places, we are not narrating history but studying a special phase of evolution. It matters not for us that no university invited Leonardo to its halls, and that his science was valued by his contemporaries only as an adjunct to the art of engineering. The great fact still is that he was the first of mankind to propound laws of motion. It is not for anything in Luther's doctrines that he finds a place in our scheme. No matter for us whether they were sound or not. What he did toward the evolution of the scientific investigator was to show by his example that a man might question the best established and most venerable authority and still live, still preserve his intellectual integrity, still command a hearing from nations and their rulers. It matters not for us whether Columbus ever knew that he had discovered a new continent. His work was to teach

that neither hydra, chimera, nor abyss—neither divine injunction nor infernal machination—was in the way of men visiting every part of the globe, and that the problem of conquering the world reduced itself to one of sails and rigging, hull and compass. The better part of Copernicus was to direct man to a point of view whence he should see that the heavens were of like matter with the earth. All this done, the acorn was planted from which the oak of our civilization should spring. The mad quest for gold which followed the discovery of Columbus, the questionings which absorbed the attention of the learned, the indignation excited by the seeming vagaries of a Paracelsus, the fear and trembling lest the strange doctrine of Copernicus should undermine the faith of centuries, were all helps to the germination of the seed,—stimuli to thought which urged it on to explore the new fields opened up to its occupation. This given, all that has since followed came out in regular order of development, and need be here considered only in those phases having a special relation to the purpose of our present meeting.

So slow was the growth at first that the sixteenth century may scarcely have recognized the inauguration of a new era. Torricelli and Benedetti were of the third generation after Leonardo, and Galileo, the first to make a substantial advance upon his theory, was born more than a century after him. In a a generation there appeared only two or three men who, working alone, could make real progress in discovery, and even these could do little in leaven-

ing the minds of their fellowmen with the new ideas.

Up to the middle of the seventeenth century an agent which all experience since that time shows to be necessary to the most productive intellectual activity was wanting. This was the attrition of like minds, making suggestions to each other, criticising, comparing, and reasoning. This element was introduced by the organization of the Royal Society of London and the Academy of Sciences of Paris.

The members of these two bodies seem like ingenius youth suddenly thrown into a new world of interesting objects, the purposes and relations of which they had to discover. The novelty of the situation is strikingly shown in the questions which occupied the minds of the incipient investigators. One natural result of British maritime enterprise was that the aspirations of the Fellows of the Royal Society were not confined to any continent or hemisphere. Inquiries were sent all the way to Batavia to know "whether there be a hill in Sumatra which burneth continually, and a fountain which runneth pure balsam." The astronomical precision with which it seemed possible that physiological operations might go on was evinced by the inquiry whether the Indians can so prepare the stupefying herb *Datura* that "they make it lie several days, months, years, according as they will, in a man's body without doing him any harm, and at the end kill him without missing an hour's time." Of this continent one of the inquiries was whether there is a tree in

Mexico that yields water, wine, vinegar, milk, honey, wax, thread, and needles.

Among the problems before the Paris Academy of Sciences those of physiology and biology took a prominent place. The distillation of compounds had long been practiced, and the fact that the more spirituous elements of certain substances were thus separated naturally led to the question whether the essential essences of life might not be discoverable in the same way. In order that all might participate in the experiments, they were conducted in open session of the Academy, thus guarding against the danger of any one member obtaining for his exclusive personal use a possible elixir of life. A wide range of the animal and vegetable kingdom, including cats, dogs, and birds of various species, was thus analyzed. The practice of dissection was introduced on a large scale. That of the cadaver of an elephant occupied several sessions, and was of such interest that the monarch himself was a spectator.

To the same epoch with the formation and first work of these two bodies belongs the invention of a mathematical method which in its importance to the advance of exact science may be classed with the invention of the alphabet in its relation to the progress of society at large. The use of algebraic symbols to represent quantities had its origin before the commencement of the new era and gradually grew into a highly developed form during the first two centuries of that era. But this method could represent quantities only as fixed. It is true that the

elasticity inherent in the use of such symbols permitted their being applied to any and every quantity; yet, in any one application, the quantity was considered as fixed and definite. But most of the magnitudes of Nature are in a state of continual variation; indeed, since all motion is variation, the latter is a universal characteristic of all phenomena. No serious advance could be made in the application of algebraic language to the expression of physical phenomena until it could be so extended as to express variation in quantities, as well as the quantities themselves. This extension, worked out independently by Newton and Leibnitz, may be classed as the most fruitful conception in exact science. With it the way was opened for the unimpeded and continually accelerated progress of the two last centuries.

The feature of this period which has the closest relation to the purpose of our coming together is the seemingly endless subdivision of knowledge into specialties, many of which are becoming so minute and so isolated that they seem to have no interest for any but their few pursuers. Happily science itself has afforded a corrective for its own tendency in this direction. The careful thinker will see that in these seemingly divergent branches common elements and common principles are coming more and more to light. There is an increasing recognition of methods of research and of deduction which are common to large branches or to the whole of science. We are more and more recognizing the principle that progress in knowledge implies its reduction to

more exact forms and the expression of its ideas in language more or less mathematical. The problem before the organizers of this Congress was, therefore, to bring the sciences together and to seek for the unity which we believe underlies their infinite diversity.

The assembling of such a body as now fills this hall was scarcely possible in any preceding generation, and is made possible now only through the agency of science itself. It differs from all preceding international meetings in the universality of its scope, which aims to include the whole of knowledge. It is unique in that none but leaders have been sought as members. It is unique in that so many lands have delegated their choicest intellects to carry on its work. They come from the country to which our Republic is indebted for a third of its territory, including the ground on which we stand; from the land which has taught us that the most scholarly devotion to the languages and learning of the cloistered past is compatible with leadership in the practical application of modern science to the arts of life; from the island whose language and literature have found a new field and a vigorous growth in this region; from the last seat of the Holy Roman Empire; from the country which, remembering a monarch who made an astronomical observation at the Greenwich Observatory, has enthroned science in one of the highest places in its government; from the peninsula so learned that we have invited one of its scholars to come to tell us of our own lan-

guage; from the land which gave birth to Leonardo, Galileo, Torricelli, Columbus, Volta—what an array of immortal names!—from the little republic of glorious history which, breeding men rugged as its eternal snow peaks, has yet been the seat of scientific investigation since the day of the Bernoullis; from the land whose heroic dwellers did not hesitate to use the ocean itself to protect it against invaders, and which now makes us marvel at the amount of erudition compressed within its little area; from the nation across the Pacific, which, by half a century of unequaled progress in the arts of life, has made an important contribution to evolutionary science through demonstrating the falsity of the theory that the most ancient races are doomed to be left in the rear of the advancing age—in a word, from every great center of intellectual activity on the globe, I see before me eminent representatives of that world advance in knowledge which we have met to celebrate. May we not confidently hope that the discussions of such an assemblage will prove pregnant of a future for science which shall outshine even its brilliant past?

II

SCIENCE IN THE INDUSTRIAL REVOLUTION

CECIL HENRY DESCH

[THE extent to which science has contributed to the development of engineering is indicated by the following survey. The author, Cecil Henry Desch (1874–), President of the Faraday Society, was educated at Finsburg Technical Colege, Würzburg University, and University College, London. He has served on the faculties of King's College, London, the University of Glasgow, and the Royal Technical College, Glasgow. Since 1920 he has been Professor of Metallurgy in the University of Sheffield. A consultant of wide experience, he is also the author of numerous books and articles on chemistry, metallography, metallurgy, and sociology. His sketch—in essence, a history of engineering—forms one of the chapters in an interesting anthology, *Science and Civilization* (1923), edited by Francis Sydney Marvin (1863–), a brilliant student of education and philosophy. It is reprinted by special arrangement with the publishers, the Oxford University Press.]

To study the share of science in bringing about the great social change toward the end of the eighteenth century that we know as the Industrial Revolution is to turn from a time when science was the concern of a few intellectual leaders, and occasion-

ally the amusement of a group of amateurs, to one when it came to affect the life of every member, even the least instructed, of the Western communities. It is to turn from isolated experiments in the harnessing of the forces of Nature to man's needs to a deliberate conquest and exploitation of those forces in the service of industry. We may observe the distinction that has been drawn between the Industrial and the Mechanical Revolution, closely connected in history though they are. There is much evidence to show that the transition from domestic workshops to factories, and from small-scale handicrafts to capitalist production, was in course of taking place independently of machines; but the whole movement was hastened and intensified to a most remarkable extent by the new mastery of Nature that came with the introduction of coal as a metallurgical fuel and with the invention of the steam engine. These two great inventions led to a complete transformation of industry. Not only was its character radically changed, but the distribution of population was altered by the establishment of the growing industries on the coal fields, ignoring previous historical conditions, so that new centers of dense population grew up, hastily and without forethought, presenting those undesirable features that we commonly associate with the idea of the Industrial Revolution. For the moment we have to deal only with the main outlines of that transformation, attempting to relate it to the progress of science.

We should be wrong to suppose that organized

industry on a large scale was a new thing in the history of the world. The canal system of Babylonia, the pyramids of Egypt, the great aqueducts of Roman cities, were achievements in construction comparable with any but the greatest works of modern times, demanding not only a vast supply of human labor, which the institution of slavery made possible, but also a high degree of engineering knowledge and skill. It is difficult to picture the task of the ancient engineer, with primitive surveying instruments, cumbrous methods of calculation, and only the rudest of mechanical appliances for handling large masses of material. Nevertheless, the results achieved were marvelous, and modern engineers are beginning to study, with renewed interest, the methods adopted by their predecessors of Egypt and Rome. Neither was their work purely empirical. The ancient studies of geometry and physics were originally directed to practical ends, and some of the most important ancient discoveries in abstract science arose from attempts to solve the urgent practical problems of the land surveyor and the engineer. Simple mechanical devices which form the basis of elaborate mechanisms, such as the wheel and the lever, were known and commonly applied, whilst the labors of Archimedes and others had established the quantitative laws of some of them, notably of the lever. At a later date, the sea defenses of Venice and Holland, which made it possible for those states to rise to power and commercial importance in spite of geographically unfavorable conditions, may be

named along with the great engineering works of Rome. We may place the pyramids, as royal tombs, in a class apart, but all the other structures named had the character of public works, carried out under the authority of states or cities for the benefit of the general body of citizens. The mediæval cathedrals are a most wonderful example of such coöperative work on a large scale, combining majesty of conception, skill in constructional design, and resourcefulness in overcoming technical difficulties. It was not new for large numbers of men to work together on a single task, or to employ mechanical appliances for the purpose, but it was new for goods for the market to be produced in this way. Capitalism was not new; contractors were often responsible for the undertaking of those great works of ancient times, and certain industries, such as iron smelting, were capitalistic in their organization from early times, but the production of ordinary goods in quantity for private profit was, with some exceptions, unknown before the eighteenth century. At that time, the textile industries and a few others started their new career, to be hastened almost inconceivably in their transformation before the century was out by the application of improved machines and more efficient mechanical power.

The spirit of invention, again, which seems to us so typical of the Industrial Revolution, was no new thing in human history. Among the Greeks, such legends as that of Dædalus commemorate the inventors of new crafts, of casting and hammering

metals, of erecting buildings, and of constructing military engines. Hero of Alexandria, with his primitive steam engine and other scientific toys, as well as his serious military devices, is a witness to the existence of the capacity for designing elaborate mechanisms in the first century A.D., and Vitruvius, in the same century, in his descriptions of cranes and machines, now and then seems oddly to anticipate modern inventions, as when he describes a taxicab, the distance traveled by a chariot being measured by the number of balls dropped into a bowl, each ball being released after a certain number of revolutions of the wheels. To come to later times, Leonardo da Vinci, one of the most marvelous men of genius in history, was a most fertile inventor, and his notebooks, most of which have only become known recently, contain sketches and designs of machines for the most varied purposes. I need only mention a machine for cutting the teeth of files, an operation even now largely performed by hand. Many inventors, from Hero to Vaucanson, busied themselves with the construction of ingenious automata, imitating the action of men or animals, some of them exhibiting a high degree of manual skill and fertility of invention.

None of these inventions had any appreciable influence on industry. In looking for an explanation of this, we may note that, with the exception of Leonardo da Vinci, who was far in advance of his time, so that his projects could not be carried out until industry had made much further progress, in-

ventors had confined themselves to two main classes of objects. Either their machines were built up of timbers, with at most small connecting parts of metal, like the military engines, storming towers, and catapults of the ancients, or the water wheels of mediæval industry, or they were delicate mechanisms, like the automata of Vaucanson, calling for ingenuity and dexterity, but making no severe demands on the strength or quality of the materials used in them. Machines of the modern kind become possible only when the art of working large masses of metal has reached a high state of development. Broadly speaking, this was not the case before the latter part of the eighteenth century. There have been exceptions: the ancient Indian iron forgings, although they were limited to pillars and simple beams, still excite our admiration, and the art of casting bronze for statuary arrived at extraordinary perfection even in early Greek times, and was preserved and perfected by the great German and Italian masters of the Renaisssance, as Peter Vischer of Nuremberg and Benvenuto Cellini. The casting of iron was limited to comparatively small masses, cannon being the largest, and forging to still smaller masses, such as could be dealt with by a tilt hammer worked by water power. The Metallurgical Revolution had to precede the Mechanical, and it was not until iron could be handled in quantity with ease and certainty that a machine, however ingenious, had a chance of becoming a practical success.

The smelting of iron had been performed from

prehistoric times, in a simple manner, by heating the ore with charcoal in a primitive furnace, urged to a sufficiently high temperature by a blast, the bellows being driven by hand or later by water power. With only slight modifications, this process persisted for many centuries. It was only suitable for pure ores and for small quantities, and the special skill required for the operation combined with certain elements in social tradition to place the smith in a place apart, as is shown by legends and folk tales in many countries. From the time of the Romans onwards, the process was improved by almost imperceptible steps, due to inventors of whom we know next to nothing. The most that we can do is to trace, partly in documents but chiefly in such material remains as the destructive action of time has left to us, the passage of a new metallurgical process across Europe. Some of the most important improvements in the smelting of iron probably came to us from the Walloon country in the east of Belgium. A few men of real scientific ability devoted themselves to the study of metals, chief amongst them being Georg Bauer, or Agricola, to whom we owe a magnificent treatise, published in 1556, in which we have clearly set forth the processes of mining and smelting then in use, with such scientific explanations as were then possible. Agricola is wonderfully modern in his outlook, and his rejection of alchemy and of all far-fetched theories of the origin of minerals in itself entitles him to an honorable place in the history of science. For a complete understanding of metal-

lurgical processes a knowledge of chemistry is necessary, so that a truly scientific control of the industry was not possible until much later.

To fix our ideas, we may consider the state of the English iron industry in the latter part of the sixteenth century. The principal region was the Weald, most of the works lying in Sussex, with extensions into Surrey and Kent. Here blast furnaces, worked by means of charcoal, made the cast iron, and when malleable material was wanted, the same fuel was used for the conversion. Water power was necessary to blow the furnaces and to drive the forging hammers. The consumption of wood for charcoal was large, so that even in 1558 a statute was passed to prevent the destruction of forests for this purpose. At first Sussex was exempted, but later the prohibition was extended, and the movement of the industry to the Forest of Dean, another old smelting center, took place. There was a constant strife between the claims of the state, which required timber especially for shipbuilding purposes, and the needs of the growing iron industry. By the beginning of the eighteenth century the scarcity of wood in England was so serious that the ironmasters of the Furness district of Cumberland were erecting works in the Scottish Highlands, where timber was still to be found and the restrictions did not apply.

In the face of these difficulties, it is not surprising that attempts were made to replace charcoal by coal, already long a familiar domestic fuel. Dud Dudley, in the middle of the seventeenth century, was the

most successful of these experimenters, but the jealousy of his rivals put an end to his work; and it was not until 1757 that coal, previously converted into coke, was successfully used in blast furnaces at Coalbrookedale, in Shropshire, where also the first cast iron bridge and the first iron rails for mine trams, in place of wood, were used. This change marks a turning point in industrial history. The greater cheapness and facility of coal made the manufacture of iron (steel was still made only on a very small scale) possible, and thus began the migration of industry to the coal fields, which has led to the present distribution of the population, so different from that of the era preceding coal. The time was now ripe for the Mechanical Revolution.

Mechanical power, for driving corn mills and forge hammers, for blowing furnaces, and for grinding cutlery, had been hitherto derived from the wind or from the fall of water to a lower level. The wind is too variable to be applied widely, and windmills are possible only in flat countries; but water power has wide applications. We can imagine how a great industrial civilization might have grown up, organized for production on a large scale, and based on water power. The use of the water wheel was common throughout Europe, and the extension would have been a natural one. The damming of streams to form "hammer ponds," each supplying a wheel, was characteristic of iron-working districts, and the corn mill has been a feature of agricultural life for centuries. But practical difficulties stood in the way

of any such development. The very power of great waterfalls, such as the Falls of the Rhine at Schaffhausen, made it impossible to utilize them. The simple water wheel, built up of timbers, however skillfully constructed, would have been crushed by the mass of falling water, and all that man could do with such a source of power was to lead off some minute fraction through a channel to supply a single wheel. Only a modern turbine, scientifically designed to take the full force of the water, and constructed of materials of exceptional strength, can serve in such a case; and for that neither the knowledge nor the means existed. Had the invention of the water turbine preceded that of the steam engine, the geographical distribution of industry would have been far other than it is. The other great natural source of power—the tides and the direct heat of the sun—have so far baffled even the engineers of our own day.

Thus, of the natural sources of power now known to us, there only remained the combustion of fuel. To convert the chemical energy of wood or coal into mechanical energy is not directly practicable, and the suggestion would never have occurred to an early inventor, since the very conception of energy, and of the mutual equivalence of different kinds of energy, did not arise until after the date of the Industrial Revolution. We may consider the scientific knowledge that was available in the period immediately before the invention of the steam engine. The laws of statics, the simplest of which had been es-

tablished by Archimedes both for solids and for liquids, were extended by Stevin of Bruges and later by Galileo, who is also the true founder of dynamics. The great work of Newton had brought mechanics to such a state of perfection that the most difficult problems in connection with bodies at rest or in motion could be solved, with the aid of the new mathematical methods due to Napier, Descartes, Newton, and Leibnitz. The study of gases was of more recent origin. Ctesibius of Alexandria, the teacher of Hero, is credited with the first scientific studies of air and steam, and the expansive force of gases was known to him, but it is with the work of Torricelli and Boyle that a firm foundation for a knowledge of the properties of gases, including steam, is first apparent. Boyle, one of the most brilliant of that group of men who established the Royal Society, and so gave practical form to the new creed of experiment as the true means of investigating Nature that was making its way in England, added more than any other man to our knowledge in this field. By discovering the relation between the volume of a gas and the pressure to which it was subjected, he made it possible to define quantitatively the behavior of an enclosed volume of gas under different conditions.

The scientific knowledge required for the construction of a simple steam engine was in existence by the middle of the seventeenth century, but it was long before it was practically applied. Among the devices of Hero of Alexandria had been a machine,

capable of performing simple motions, which depended on the expansion of air in a partly closed vessel, forcing water into another vessel, and it was this contrivance that formed the model for the earlier inventors. Della Porta, in 1601, replaced air by steam, and suggested that the condensation of the steam might be utilized in drawing up water from below. De Caus and the Marquis of Worcester suggested similar machines, pumps rather than engines, intended for the lifting of water, but none of these ever assumed practical shape. It was not until 1698 that Thomas Savery made a working steam engine on this principle, involving several ingenious details, and finding direct application in the pumping of water from mines, a question then beginning to assume importance. As the metallurgical demand for coal increased, shallow workings became insufficient, and miners were prevented from working at greater depths by the accumulation of water in the mines. Savery's engine worked with pressure sometimes as high as eight or ten atmospheres, and naturally gave much trouble from leakage. In principle it was not unlike the modern pulsometer pump.

Denis Papin, in 1690, adopted an entirely different principle. The use of a piston moving in a cylinder was already familiar in the common suction pump, and Papin, by condensing steam in the lower part of the cylinder, caused the piston to descend by atmospheric pressure. Huygens had shortly before proposed an explosion engine with piston, a crude forerunner of the modern internal combustion en-

gine. Neither had any practical consequences. Newcomen, in 1705, constructed a steam pumping engine which held the field for the greater part of the century. He used a piston, but made the boiler for generating steam a separate vessel from the cylinder, and brought about the condensation of the steam by admitting a jet of water. The piston rod moved one end of a beam, to the other end of which was attached the pump rod, and in this form the movement of the necessary valves soon being made automatic by connecting them with the beam, the machine was long employed for raising water from mines. One is even now in use in the Sheffield district. Many of these engines were built at Coalbrookedale. Great strength was not required, as the pressure never differed greatly from that of the atmosphere.

So far the engines had all been examples of mechanical ingenuity, involving no new principles, and based only on the simplest mechanics. The next great step was not taken at random, but was the result of the application of new principles. James Watt was much more than a merely ingenious mechanic. Skilled workman as he was, he was the close friend of two active investigators in physics, Black and Robison, and with them and others of like intellectual standing he discussed his inventions. Struck by the inefficiency and wastefulness of the Newcomen engine, he rightly saw that this came from the alternate heating and cooling of the cylinder. Black's discovery of latent heat had shown how large a quantity of heat is released when steam

is condensed to water, and Watt, applying this knowledge, took the decisive step of separating the cylinder from the condensing vessel. This is not a memoir on the steam engine, and it is impossible to enter into the wonderful record of Watt as an inventor, adding detail after detail until the crude steam pump had been converted into an efficient engine, the reciprocating action of the piston being converted into rotary motion by means of the crank, so making it possible to employ the steam engine to drive machinery in a factory or, as was done later, to fix it into a boat for steam navigation, or on wheels as a locomotive. Subsequent developments, remarkable as they have been, are essentially matters of detail.

Before leaving this subject, a suggestion of Giovanni Branca in 1629 may be mentioned. This was to direct a jet of steam against the vanes of a wheel, and so produce rotation. This suggestion bore no fruit, but it is interesting in the light of recent mechanical history. Many inventors from time to time reverted to the idea of a steam turbine, but the plan proved to be unrealizable. The high speed of such an engine was a practical difficulty, whilst the principles were yet unknown. The theory of the heat engine, according to which the maximum efficiency of the most perfect engine is limited by the temperatures between which it works, was only established in 1824, by Sadi Carnot. Carnot showed that heat does work when it falls from a higher level (of temperature) to a lower, but that an equivalent quantity of heat disappears in the process was not

realized until the establishment of the doctrine of the conservation of energy in 1843 and succeeding years by the labors of Joule, Mayer, and Helmholtz. It is this doctrine that controls the efforts of modern inventors, and makes immediately evident the absurdity of proposals to increase the amount of energy in a system without taking it from somewhere else. A lack of comprehension of this principle is responsible for many fallacious suggestions. The steam turbine is a quite modern invention, scarcely forty years old, and is based on a most thorough study of the properties of steam, as well as of those of metals used in its construction. It could never have been arrived at by a process of happy guessing, or of trial and error.

Watt's engine could not have been constructed at an earlier period. It was not a pump, but an engine in the modern sense, and required not only relatively large masses of metal, but accurate casting and boring, things that could not yet be obtained. On reading the life of Watt, one is struck by the great practical obstacles that confronted him at every stage. Although his early engines were atmospheric, depending on the vacuum produced by condensing the steam for their action, so that high pressures were unnecessary, his cylinders had to be large to give sufficient power, and even when the casting difficulties had been overcome there was the difficulty of boring the cylinder so that the piston would make a reasonably tight fit. Gradually, Watt and his associates triumphed over their difficulties, and after

many years of effort and discouragement the steam engine became the agent of the Mechanical Revolution. The same metallurgical advances that had created the demand for engines for pumping, on account of their large consumption of coal, made it possible for the engines to be constructed. The Carron works in Scotland, with which Watt was associated through Roebuck, assisted him in the manufacture of them as well as by making use of them when made.

In the meantime, a revolution in the manufacture of textile materials had been going on in this country. Hargreaves, Arkwright, and Crompton had invented machines, depending on no new principle, but ingeniously combining simple mechanical movements, which could replace hand labor and allow of the production of textile fabrics on an enormously increased scale. Whilst the machines were at first driven by water power, and the mills were therefore placed near to streams having a sufficient fall, the usefulness of steam power for the purpose was soon obvious; and in 1785 the first steam cotton mill was set to work in Nottingham.

Factory production on a large scale was first adopted in the metal industry. The iron and steel works of Abraham Crowley at Newcastle employed several hundred men in 1682. There had been textile capitalists employing as many persons much earlier, but their workers were scattered through small domestic workshops, and not collected into a single factory. With the invention of power machin-

ery for spinning and weaving textiles came the organization of that industry also on a factory plan, and the engineering industry followed as a consequence. The change having once set in proceeded with ever increasing velocity, until the present conditions of industry were reached. In the great majority of manufactures, machine production has superseded hand work, whilst the immense developments of mechanical transport have transformed the conditions of industrial life throughout.

Not all industries were affected to an equal extent. As we have seen, the invention and construction of the steam engine and of the machinery for textiles demanded knowledge which was supplied by the sciences of mechanics and physics, already sufficiently advanced by the middle of the eighteenth century. Scientific chemistry is considered to date only from the time of Lavoisier, so that the transformation of the chemical industries, formerly exceedingly primitive, came much later, and in fact is only now in progress. Agriculture was improved, but for any radical transformation a scientific knowledge of biology was needed, and that is of quite modern growth. We are still only perceiving the first fruits of the systematic application of biological science to agriculture, a reformation which may well transform rural life, and to some extent counteract the evil influences of the Industrial Revolution.

Those evils were immense. The introduction of steam power almost immediately opened the way to the rapid and cheap production of many classes of

goods. It was found that large profits could be made by employing labor in great factories. Competition became intense, and to secure a remunerative share of any manufacture the costs of production had to be kept as low as possible; hence the misery and cruelty of the late eighteenth and early nineteenth centuries. Unfortunately, the growth of facilities for manufacture was far too rapid for the essential social readjustments to keep pace with it, and evils accumulated fast. Moreover, the new discoveries came at a time when the moral sense, in this country at least, was of a low standard. Even admirers of the eighteenth century must admit that a selfish complacency was characteristic of much of its life, and that the influence of religion on morality was then at its lowest ebb. It may seem a paradox that the Methodist Movement and the Evangelical Revival did practically nothing to counteract the selfishness of the new industrial era. It is remarkable that even Hannah Moore, in her accounts of her endeavors to promote a knowledge of the Bible among the poor, scarcely betrays a suspicion that the condition of the industry of her time, with its appalling misery for a large proportion of the workers, was anything but a natural and inevitable state of affairs; and her complacent reflections on the good fortune of the rich are to a modern reader strangely heartless. The fact is that the new religious fervor was so directly and intensely concerned with a future life that its influence in improving the conditions of this world was almost insignificant. A curious nar-

rowness is perceptible in the attitude of some even of the most earnest of religious philanthropists at a somewhat later date. The leaders of the movement for the abolition of the slave trade, with a few honorable exceptions, took little notice of the virtual slavery and misery of the industrial population of our own country. The influence of the churches and the sects was small, and when the means of acquiring wealth rapidly presented themselves, there was no restraining force of adequate strength to oppose the greed of the new industrial chiefs. Dickens' Mr. Gradgrind, although later in date, is a typical figure of the age. Suitably controlled, we can picture a mechanical revolution which would have rendered life infinitely happier, by improving comfort and lessening toil, without imposing a practical slavery on large masses of workers, or converting great tracts of beautiful country into hideous wildernesses, as has been the case in the North. Mr. Austin Freeman has made a good point in remarking that the introduction of machinery, whilst it has destroyed many handicrafts and turned many classes of skilled craftsmen into soulless machines, has done but little to remove the drudgery of everyday life, so that men are still employed in the roughest of mechanical tasks that might well be performed by machines, and the housewife has derived little benefit in her daily toil from all the inventions of the Mechanical Age. This is true, and whilst it emphasizes some of the lessons preached so eloquently and so fruitlessly by Ruskin, it points a way to possible reforms in the future.

One of the worst features of the Industrial Revolution is the wasteful treatment of natural resources. In the first enthusiasm of the discovery of steam power, it seemed that Nature had placed in the hands of man an inexhaustible source of wealth. Coal was abundant in England, and the idea of its possible exhaustion did not present itself to the minds of those who used it. Whole counties were laid waste in order that goods might be produced cheaply, whilst smoke and slag heaps were allowed to disfigure the country. Professor Geddes has rightly said that the Industrial Age must be divided into two, a Palæotechnic and a Neotechnic Age, in the first of which natural resources were squandered and social good subordinated to private gain, whilst in the second those conditions are reversed. We are only now seeing the beginning of the Neotechnic Age.

It would be wrong to blame science for the evils of industrialism. It was scientific discovery, misapplied in practice, that made those evils possible, but the spirit of industrial greed was not that of science. In another aspect, also, it was the imperfection of science that led to its misapplication. The waste of natural resources could hardly have been so great had the idea of the conservation of energy been present to men's minds. It was of later growth, and was not in time to prevent the evils. Even now it is so little comprehended by the ordinary man of business that his actions are hardly affected by it. Further, the scientific study of human physiology came

too late to warn men of the consequences of the unhealthy conditions of industrial life, whilst the fact that social science had not yet come into existence was the most potent of all in permitting such outrages on social good as characterized the system. Science, that is, the mechanics and physics of the time of Watt, might have been used to increase the sum of human happiness, and it is not the fault of science that it was not so used. Science is not responsible for its misuse by selfish men. In the last few years the cry has again been raised that materialistic science is responsible for the horrors of war, because chemistry and physics have been applied to the production of more destructive and crueler means of warfare. The danger of such misapplication still exists, and has to be reckoned with. One of the great aims of physical science of the present day is to discover a means of tapping the vast store of energy contained within the atom, and revealed to us by the phenomena of radioactivity. As Professor Soddy, one of the leading workers in that field, has remarked, the first application of that discovery, should it be made, would undoubtedly be the invention of a bomb, incomparably more destructive than any hitherto known. This is a real danger, but it cannot be allowed to hinder scientific investigation. The same discovery might be used to alleviate the hardships of life and to bring about a happier social state, and we must look to the control and not to the suppression of invention for a remedy for the evils of misapplied science.

At the same time as the discoveries in mechanics and in the properties of gases, a new force was being studied, the knowledge of which was not to bear fruit until much later. It was in the year 1600 that William Gilbert, a court physician to Queen Elizabeth, published his treatise on the magnet, in which for the first time experiments on electricity and magnetism were carefully described. This great work laid the foundation of a new science, but for more than two centuries that science grew slowly, and even the brilliant discoveries of Franklin, Cavendish, and Volta had no immediate practical consequences for industry. The discoveries of Oersted and Ampère led to the invention of the electric telegraph; but it was not until Faraday, one of the greatest experimenters in the whole history of science, established the principal laws of electromagnetism, that industrial applications of electricity became possible. The dynamo and the electric motor, with their more recent companion, the electric furnace, are the instruments of a new mechanical revolution taking place before our eyes, but of which only our descendants will see the full results. Electrical power will be the chief practical means of bringing about the change from the Palæotechnic to the Neotechnic Age. One feature of its influence is to be remarked in the geographical redistribution of industries, especially in the transference of some of them from the coal fields to the mountainous regions where water power is abundant, with the attendant possi-

bility of making a fresh start, untrammeled by the surroundings of a palæotechnic industrial region.

We may note, in passing, although it belongs to a later period than that of the introduction of the steam engine, that electrical invention has pursued a rather different course from mechanical invention. Whilst the design of new mechanical devices has often been instinctive or based merely on a process of trial and error, the underlying scientific principles being established later—the steam engine was a practical success before the theory of heat engines was worked out by Carnot—the practical applications of electricity have followed on the theory. Wireless telegraphy was not the result of a happy guess or of a process of trial and error, but was a direct application of a theoretical prediction of Clerk Maxwell, tested experimentally by Hertz. The thermionic valve, which has made wireless telephony possible, is a consequence of purely scientific investigation on the emission of electrons from heated bodies,—investigations apparently remote from any practical applications. Electrical inventions are historically more recent than mechanical, and it is probable that the course of their history will be the normal one in the future, invention following on theory instead of preceding it. The time has passed when a happy guess may result in an epoch-making discovery.

The growth of mechanical industry became more and more rapid as the years of the nineteenth cen-

tury passed. Two factors in that growth may be selected for brief mention, the development of the manufacture of steel and the rise of the chemical industries. Whilst, in the period that has been considered, iron was made on a large scale in the blast furnace by the use of coke, such steel as was required was manufactured on a relatively small scale, Huntsman's crucible process of 1740 being used for the greater part of the production until the middle of the nineteenth century. Then two great inventions, that of Bessemer and that of Siemens and Martin, revolutionized the industry. The two were almost simultaneous, but the former sooner became a practical success. By blowing air through pig iron in a suitable vessel, a quantity of iron weighing several tons could be converted into steel in twenty minutes, and the scale of production increased almost immediately. From this point onward the curve which shows the annual production of steel rises with increasing steepness until 1913. The Siemens-Martin, or open-hearth process, was slower in making its way, but is now in this country by far the more important, and is everywhere gaining ground on its rival. The world's production of steel, which was about 100,000 tons in 1848, was about 76,000,000 tons in 1913. These vast quantities of cheap material have transformed the construction of buildings, bridges, and ships, and we now live in a veritable Steel Age. Metallurgical chemistry has added a wide range of alloy steels, containing nickel, chromium, tungsten, and other

metals, to the materials available to the engineer, surpassing the older steel and iron in strength and elastic qualities, and so making possible the construction of the motor car and the aeroplane.

The chemical industries are essentially of modern growth. The great alkali industry, the foundation of all the others, began with the invention of the Le Blanc soda process in 1791, and soon found a home in England, where it flourished. Popular attention, however, has been more constantly directed toward that part of the chemical industry which deals with artificial dyes and drugs, the industry of coal tar products. Scientific chemists having shown the presence of definite chemical compounds in the tar obtained in the distillation of coal, the first colored compound, mauve, was prepared from it by Perkin in 1856, since when the industry has reached an extraordinary development, many thousands of compounds having been prepared, including a wide range of synthetic coloring matters and therapeutic agents, and of such minor but yet important substances as photographic developers. The virtual capture of the industry by Germany, owing to the employment of an army of chemical investigators by the manufacturers, has caused a widespread interest in its fortunes, its social and political importance being quite disproportionate to its magnitude, which is far below that of other branches of industry. The coal tar products have formed the text of many a homily on the importance of scientific education, but it must

not be forgotten that its lessons are equally applicable to many other industries, which can only flourish and grow when scientifically controlled.

Unfortunately, the manufacture of synthetic chemicals involves more than the production of dyes and drugs. Modern high explosives belong to the same class and are derived from the same source, and whilst these, by their use in mining, have increased efficiency and diminished danger, they have made warfare more deadly and have enormously increased its scale. So, too, the knowledge of many compounds prepared in the laboratory and remarked for their noxious qualities led to the introduction in the Great War of "poison gases," the last refinement of horror in fighting. These are among the misuses to which all scientific discoveries are liable to be put as long as the general conscience is insufficiently powerful to control them.

Closely allied to explosives, however, are the artificial fertilizers by means of which the yield of cereals and other crops can be so largely increased. By combining the experience of the chemist with that of the electrician, means have been found of converting the nitrogen of the air into compounds which serve in time of peace to increase the fertility of the land, and in time of war to form the foundation of high explosives. Hence the importance of the synthetic nitrogen industry, which requires cheap electric power, derived from water, for its existence, and therefore tends to establish itself in new districts, on the coast of Norway, among the mountains of

Central Europe, or on the shores of the Pacific. It is being followed by a number of other electrochemical industries, which associate themselves with it, and are assisting in that transfer of industry from the coal fields of which mention has already been made.

The early scenes of the Industrial Revolution were set in England, where both invention and application advanced more rapidly than elsewhere. For many years other nations were content to follow at an interval the path traced out by British industry. It was only later that they became serious rivals, and the struggle for industrial supremacy belongs to a later period than that considered in this essay. There were several reasons for this industrial leadership of England. Her supremacy in shipping and in foreign trade had given the people an active interest in industrial production, and stable political conditions had favored the growth of a large industrial population, including many skilled craftsmen. When the change in the manufacture of iron took place, coal, iron-stone, and fireclay were found together in abundance in the North, giving this country a great natural advantage at the start. It is remarkable how, as each successive development arose, suitable raw materials were found conveniently placed,—clay for steel crucibles, ganister for the Bessemer process, and so on.

But these material factors are not sufficient in themselves to account for the British leadership in the Industrial Revolution. There was a practical

bias of the English intellect that also played its part. The experimental method of investigation, although splendidly represented in Italy by Leonardo da Vinci and Galileo, is most characteristic of English science, from Roger Bacon onward. It is commonly associated with his later namesake, but the name of Francis Bacon was rather a rallying cry for the school than anything more. The strict Baconian method, as expounded in detail by its author, was barren of results, although the general principle was an inspiration; and the real founders of the experimental school were Boyle and the men who established the Royal Society. They fought under the banner of Bacon, but their methods were their own, and it was their work, interpreted by Voltaire and d'Alembert, that influenced Continental science. The philosophy of Locke had a practical tendency, and whilst French speculative thought in the eighteenth century took mainly a political direction, that of England was essentially practical.

That the advocates of experimental investigation looked deliberately to industrial applications of their discoveries may be made clear by quoting a passage from Bishop Thomas Sprat's *History of the Royal Society*, published in 1667. Sprat was one of the founders of the Society, and his essay is a powerful defense of the experimental method against criticisms from the philosophical and religious points of view. After showing how inventions have mostly arisen from one of three causes—chance, the desire of pleasure or luxury, and necessity—he goes on to

show that the study of experimental philosophy, as he calls it, provides a more excellent way:

It is impossible for us to administer this *power* (of dominion over Nature) aright, unless we prefer the light of men of *Knowledge,* to be a constant overseer, and director of the *industry,* and *Works* of those that labor. The Benefits are vast, that will appear upon this conjunction. By this means the *Inventions* of *chance* will be spread into all their various uses, and multiply'd into many new advantages: By this the *Productions* of *necessity,* will be amplify'd, and compleated: by this those of *Luxury,* and *Wantoness* may be reduc'd to some solid ends: By this may be rays'd almost as certain a Method to invent new *Mechanics,* as now any particular *Mechanics* can practise, to produce their own *Operations*. . . . By this that will be amended, which has bin hitherto the misfortune of such *Inventions,* that they have commonly fallen into mens hands, who understood not their *Natures, uses,* or *improvements*: By this the conceptions of men of *Knowledge,* which are wont to soar too high, will be made to descend into the *material World*: And the flegmatick imaginations of men of *Trade,* which use to grovell too much on the ground, will be exalted.

We have seen that the Industrial Revolution was the consequence of the new movements in science and philosophy. Without the discoveries in mechanics and physics of the seventeenth century, the methods of industry could not have been transformed in the eighteenth. That the social consequences of the change were in large measure disastrous, and that a period of callous cruelty almost unexampled in history followed on an invention that might have brought material comfort to all, is to be attributed to the low standard of morality then prevailing, to a temporary retrograde movement in religion, and

to the fact that the practical development of the physical sciences had outstripped the growth of abstract science. Biology was scarcely born, sociology had hardly been dreamed of as a science. In the great transition that is before us, from the selfish, wasteful, and ugly Palæotechnic Age to the peaceful organization of Neotechnic industry, all the sciences will have to take their part. Some of the most ardent advocates of the claims of science to be the guide of national and social life are apt to restrict the scope of science too narrowly, including in it only the physical aspects of the universe, perhaps adding the study of the animal and vegetable world. Viewed so narrowly, science is dangerously open to misapplication in the cause of commercial interests or of military ambitions, and it is only when its scope is so extended as to include the life of man in society that the reproach can be avoided. The conception of science as a whole, ranging from mathematics to sociology and ethics, is the true safeguard against the misuse in anti-social ways.

THE TYPES OF ENGINEERING EDUCATION

III

THE ENGINEER

JOHN HAYS HAMMOND

[In *The Engineer* (1921 and 1924), a volume devoted to engineering education, John Hays Hammond (1855–) has drawn generously upon his professional experiences. After being graduated from the Sheffield Scientific School and the School of Mines, Freiburg, Germany, he joined the United States Geological Survey. Later, as a consulting engineer, he examined properties in all parts of the world. Finally, in 1900, after a colorful career in the Transvaal, he returned to the United States, where he has devoted himself to his mining interests and to hydro-electric enterprises and irrigation projects. In spite of these activities, he has lectured at several universities and has served as chairman of various commissions. His exposition of the qualities likely to lead to success in engineering is an abridgment—indicated by double spacing—of the third and fourth chapters of *The Engineer*. These qualities, Dr. Hammond insists, are more significant than "a superficial fondness for adventure, a desire to 'get rich quick,' a boyish interest in machinery," or "an aptness at mathematics." The selection is reprinted by permission of the publishers, Charles Scribner's Sons.]

I

The important qualities with which Nature must have endowed the prospective engineer are imagination, integrity of purpose, accuracy of thought, capacity for judgment, ingenuity, curiosity, the crea-

tive instinct, and an innate interest in the workings of natural laws. These are the essentials. There are, of course, special aptitudes for the special branches, and there are a large number of qualities which may be acquired, and which I shall describe in the next chapter; but a man who has these essentials need have no fear of making a mistake if he takes up engineering as his life-work.

Nothing is more false than the more or less prevailing belief that imagination is useful only to the poet, artist, or philosopher, and should be suppressed by the practical man as dangerous. The engineer, practical as he is, must at the same time be as much a dreamer as any of these if his work is of any magnitude. He must have the power to see a thing before it exists. In all his work of inventing and planning he must be able to see a need and its remedy before the need arises; he must forestall difficulties and overcome obstacles before they appear; but especially he must have the power to visualize the completed work in all its details, whether it be a new kind of valve or a suspension bridge. . . . These are dreams,—as much so as the dreams of Coleridge, or Michelangelo, or Kant. But when the dream has been formed in his mind, the engineer brings all his technical knowledge and practical experience into play and makes of it a tangible fact.

Another quality which must be innate in the engineer is honesty. No amount of brilliant and clever

argument will enable him to ignore the simplest laws of physics and mathematics. . . . One cannot juggle with the forces of Nature. All attempts to cheat Nature and get around her laws result in disaster. Facts must be faced; materials of construction must be used for purposes for which they are best fitted; efficiency must characterize the performance of a machine; analysis must prevail instead of guesswork; tradition must be abandoned in favor of absolute knowledge; reason must prevail, and law must be obeyed. A clever lawyer may be able by juggling words to persuade a jury that two and two make five, a physician can convince a perfectly healthy patient that he is ill, a writer can make his public believe the incredible; but the engineer whose figures are juggled, whose materials are imperfect, whose work is cut at the corners, can deceive no one; the bridge falls and he pays the penalty. If he makes a mistake, he cannot hope to conceal it by luck or cleverness. Luck is always on Nature's side, and she is difficult to outwit.

Honesty and accuracy of thought go hand in hand. A man who is naturally accurate in his thought is likely to be a lover of truth. This is essentially an inborn quality. Many people lack it entirely, seeming to be born with an incapacity for seeing things as they are, for realizing and understanding facts, and often for thinking and speaking the truth. Seeing the world always through the colored glasses of

his own romantic illusions, such a man has no sense of reality and little faculty for true interpretation of cause and effect. It is obvious that he can never succeed in a profession in which he works under inexorable laws which admit of no individual interpretation.

Judgment, an essential in a good engineer, may be acquired in some degree through experience; the capacity for it must be inborn. The power of making definite, accurate decisions is one which some men can never learn. With all the experience in the world, they become impotent at the moment of decision, and their judgment hesitates. Such hesitation seems to be an inherent psychological defect or weakness in character which is difficult or impossible to overcome. Men who have it seek always a compromise and cannot bring themselves to take any definite step. They are eternally "weighing the evidence on both sides" and postponing the moment of choice until they lose confidence in their own decisions. Such men should avoid the profession of engineering.

Capacity for judgment implies the ability to take in a situation at a glance, to compare two conditions, one or both of which may be imaginary, and to discriminate between them. It implies, also, a native self-confidence and a courage of convictions. It implies the ability to make quick, accurate estimates on which to base decisions. Of course the knowl-

edge necessary to all judgment comes through study and practical work, as I shall explain further in the next chapter, when I describe some of the ways in which judgment is used.

The words engineer and ingenuity have the same origin. Ingenuity, which includes resourcefulness and adaptability, is a real essential. The conditions under which an engineer has started work may change so that he is obliged to alter his entire plan when it is half way completed. Landslides, earthquakes, cave-ins, upset the work of the civil or railroad engineer; the mechanical engineer is often obliged to make changes during his work, because he has found too much friction and too little efficiency, in the working parts of his machine. Examples may be multiplied indefinitely, because there is no professsion in which there are so many difficulties to be overcome during any sort of experimental or preliminary work. The joy of conquering these obstacles is one of the incentives of the profession. The development of the gas engine, the aeroplane, the wireless telegraph—in fact, any of the inventions of the past century—shows a continuous succession of improvements, the results of inexhaustible engineering ingenuity, pressed by necessity.

The engineer must have a strong creative desire. By instinct he must want to produce and construct, to create something where nothing was before, to watch it grow under his hands, to take pride in it

as originating within himself. The engineer has much the same impulse as the artist. His canal, machine, or formula is as truly the creature of his brain as is the sculptor's statue, the composer's sonata, or the writer's story. It is this impulse that so dignifies his profession and differentiates it from one limited by tradition, convention, and man-made rules. However rigid the laws of Nature, they are far broader than any code which man can construct, and permit an infinite number of combinations.

II

Besides. . . . the native virtues of the engineer, there are a large number of other characteristics which come to him as the fruits of his training. These are accuracy of practice, judgment, inventive ability, thinking ahead, the ability to analyze and to estimate, handling men, patience, and concentration. At first glance the list looks very like my summary of the inborn qualities; as I describe them further, however, my distinctions will become more obvious.

First, accuracy of practice differs from accuracy of thought in that it may easily be acquired; in fact, it must be acquired through training. With all the temperamental exactness in the world, a man is bound to make mistakes in the details of his work if he has insufficient practice in the actual mechanical processes he is required to perform. The working out of data, of structural or mechanical problems . . . is accurately and efficiently done only after much re-

hearsal. The practice which gives a man the means of solving an infinite number of different problems comes first through his technical-school training and afterward through his actual professional work. The fact that a man is born with the faculty of thinking straight is a basis on which the development of accurate practice is easy. It also gives him a desire for accuracy, a willingness to spare no pains in making himself careful and exact in practice; the impulse to "check up" on all his figures becomes part of his conscience.

The capacity for judgment is part of a man's heritage, but the actual concrete judgment itself comes only from experience. For example, one would hardly trust the opinion of a schoolboy on an investment of money, yet his judgment in a baseball crisis may be infallible. He must have the capacity for judgment or he would fail even in a matter in which he is experienced, but without the necessary knowledge his capacity is of no avail. It is so with the engineer. His judgment comes only with experience. Long training and carefully acquired knowledge enable him to tell a "salted" mine from a real one no matter how clever the trick; to estimate on the strength of a dike to hold back a river flood; to tell whether or not certain rock strata are favorable to a particular piece of construction work.

Inventive ability is based on ingenuity; and while ingenuity is a natural gift, there is no doubt that the engineer who has behind him a long career of practical work is able to think more quickly of remedies

for difficulties, improvements, necessary changes suddenly imposed by changes in conditions, than a young man who has just finished his technical-school course. The more difficult his jobs, the more ingenious the engineer becomes.

In thinking ahead the engineer is like the chess-player,—always three or four moves ahead of the game. . . . To the man who has the imaginative capacity, the habit of thinking ahead comes quickly enough. It is a habit of supreme importance to the engineer.

The ability to analyze is based on the instinct of curiosity which is almost universal, but which is especially keen in men whose tastes lead them to engineering. A boy who has the promise of success in the profession is, even in childhood, intensely interested in cause and effect. We all know the type of boy who is continually asking why things happen, what makes the wheels go round, where does the thunder come from, and a dozen other questions which we often tire of answering. He has the inquiring mind; if he is keen and intelligent in his inquiries, and persistent in his desire for exact explanation, it is a distinct engineering symptom. Such a boy never sees a machine but he analyzes its parts, tracing their interactions back to the original motive cause until he is perfectly familiar with every detail. He will not tire till his instinct is satisfied and he has found out "how it works." He has the desire to analyze inborn.

The ability to estimate is entirely an acquired one, and one which any one may learn. As the expert range finder can judge closely the distance between two points because he has had so much exercise in it, so the engineer can estimate with near approximation the cost, materials, time required for construction, and capacity of a prospective bridge. The first time he does this he may hit wide of the mark, but in time he will develop great accuracy. The prospective engineer need worry very little about this easily gained power of estimating, because it will inevitably come to him in the practice of his profession.

Handling men is based on leadership, one of the elements of the engineer's personality. A born leader has native force of character and a sense of discipline; he is master of himself at all times, has a magnetic influence, and is sympathetic with his fellow men. Besides these fundamental traits, he must have learned something of human nature, human psychology, and the average human limitations. It is difficult to understand perfectly the handling of men unless one has been in their position. It is hard for a man to be a general who has never been a lieutenant. Men who begin life by commanding men but who have had no experience as subordinates are likely to be severely handicapped in this respect, though they are born with many of the qualities which characterize leaders. For this reason I advocate a period of hard manual labor for engineers to give them an opportunity to see and learn the

conditions of labor, the attitude of the laborers toward each other and toward their employer, their limitations, and the common mistakes which are made by the men who handle them. A man can easily learn these things from the bottom; he can never perfectly learn them from the top.

Patience and concentration, two essentials . . . presuppose a real interest in the subject and an ambition to succeed. To cultivate them requires a good deal of character and much effort and hard work.

IV

TWO KINDS OF EDUCATION FOR ENGINEERS

JOHN BUTLER JOHNSON

[The phases of engineering education that are likely to accentuate the qualities enumerated by Dr. Hammond are discussed with admirable clearness by John Butler Johnson (1850–1902). No one has contrasted more sharply the two kinds of competency essential to success,—*Competency to Serve* and *Competency to Appreciate and Enjoy*. Of both types Johnson was an inspiring exemplar. Educated at the University of Michigan, he became a practicing engineer, an educator, and an inventor. After serving in the United States Lake and Mississippi River Surveys, he was elected Professor of Civil Engineering in Washington University, at St. Louis, where he had charge of the timber testing laboratory of the United States, and, later, was appointed Dean of the Department of Mechanics and Engineering at the University of Wisconsin. While thus engaged, he proposed the parabolic column formula, and introduced the roller extensometer for testing materials. Though devoted to his profession, a president of the Society for the Promotion of Engineering Education, and the author of several treatises of notable merit, he made systematic effort to extend his knowledge of literature and art. The following essay is abridged, by permission of the editors, from the interesting and authoritative volume, *Addresses to Engineering Students*, published by Dr. J. A. L. Waddell and Mr. John Lyle Harrington.]

There are two general classes of competency which are generated in the schools. These are *Competency to Serve,* and *Competency to Appreciate and Enjoy.*

By competency to serve is meant the ability to perform one's due proportion of the world's work which brings to society a common benefit; which makes of this world a continually better home for the race, and which tends to fit the race for the immortal life in which it puts its trust.

By competency to appreciate and enjoy is meant the ability to understand, to appropriate, and to assimilate those great personal achievements of the past and present in the fields of the true, the beautiful, and the good which bring into our lives a kind of peace, and joy, and gratitude which can be found in no other way.

It is true that all kinds of elementary education contribute alike to both of these ends, but in higher education it is too common to choose between them rather to include them both. Since it is only service which the world is willing to pay for, it is only those competent and willing to serve a public or private utility who are compensated in a financial way. The education which brings a competency to serve, therefore, is often called utilitarian, and sometimes spoken of contemptuously as bread-and-butter education. On the other hand, the education which gives a competency to appreciate and to enjoy is commonly spoken of as a cultural education. Which kind of education is the higher and nobler, if they

must be contrasted, depends upon the point of view. If personal pleasure and happiness are the chief end and aim in life, then for those persons who have no disposition to serve, the cultural education is the more worthy of admiration and selection (conditioned of course on the bodily comforts being so far provided for as to make all financial compensations of no object to the individual). If, however, service to others is the most worthy purpose in life, and if, in addition, such service brings the greatest happiness, then the education which develops the ability to serve, in some capacity, should be regarded as the higher and more worthy. This kind of education has the further advantage that the money consideration it brings makes its possessor a self-supporting member of society instead of a drone or parasite, which those must be who cannot serve.

The higher education which leads to a life of service has been known as a professional education, as law, medicine, the ministry, teaching, and the like. These have long been known as the learned professions. A learned profession may be defined as a vocation in which scholarly accomplishments are used in the service of society, or of other individuals, for a valuable consideration. Under such a definition every new vocation in which a very considerable amount of scholarship is required for its successful prosecution, and which is placed in the service of others, must be held a learned profession. And as engineering now demands fully as great an amount of learning, or scholarship, as any other, it has al-

ready taken high rank, although as a learned profession it is scarcely half a century old. Engineering differs from all other learned professions, however, in this,—that its learning has to do only with the inanimate world, the world of dead matter and force. The materials, the laws, and the forces of Nature, and scarcely to any extent its life, are the peculiar field of the engineer. Not only is the engineer pretty thoroughly divorced from life in general, but even with the society of which he is a part his professional life has little in common. His profession is so new that it has practically no past, either of history or of literature, which merits his consideration, much less his laborious study. Neither do the ordinary social or political problems enter in any way into his sphere of operations. Natural law, dead matter, and lifeless force make up his working world; and in these he lives and moves and has his professional being. Professionally regarded, what to him is the history of his own or of other races? What have the languages and the literatures of the world of value to him? What interest has he in domestic or foreign politics, or in the various social and religious problems of the day? In short, what interest is there for him in what we now commonly include in the term "the humanities"? It must be admitted that in a professional way they have little or none. Except in modern languages, by which he obtains access to current progress in applied science, he has practically no professional interest in any of these things. His structures are made no safer, no more economical;

his prime movers, no more powerful nor efficient; his electrical wonders, no more occult nor useful; his tools, no more ingenious nor effective because of a knowledge of all these humanistic affairs. As a mere server of society, therefore, an engineer is about as good a tool without all this cultural knowledge as with it. But as a citizen, as a husband and father, as a companion, and more than all, as one's own constant, perpetual, unavoidable personality, the taking into one's life of a large knowledge of the life and thought of the world, both past and present, is an important matter indeed; and of these two kinds of education, as they affect the life work, the professional success, and the personal happiness of the engineer, I will speak more in detail.

I am here using the term engineer as including that large class of modern industrial workers who make the application of science to the needs of modern life their peculiar business and profession. A man of this class may also be called an applied scientist. Evidently he must have a large acquaintance with such sciences as surveying, physics, chemistry, geology, metallurgy, electricity, applied mechanics, kinematics, machine design, power generation and transmission, structural design, and land and water transportation. And as a common solvent of all the problems arising in these various subjects he must have an extended knowledge of mathematics, without which he would be like a sailor without compass or rudder. To the engineer mathematics is a tool of investigation, a means to an end, and not

the end itself. The same thing may be said of his physics, his chemistry, and all his other scientific studies. They are all to be made tributary to the solution of problems which may arise in his professional career. Likewise he needs a free and correct use of his mother tongue, that he may express himself clearly and forcibly both in speech and composition, and an ability to read both French and German, that he may read the current technical literature in the two other languages which are most fruitful in new and original technical matter.

We must remember, however, that the mind of the engineer is primarily a workshop, and not a warehouse or lumber room of information. Your facts are better stored in your library. Room there is not so valuable, and the information, furthermore, is better preserved. Knowledge alone is not power. The ability to use it is a latent power, and the actual use of it is a power. Instead of storing your minds with useful knowledge, therefore, store your minds with useful tools, and with a knowledge of how to use such tools. Then your minds will become mental workshops, well fitted for turning out products of untold value to your day and generation. Everything you acquire in your course in this college, therefore, you should look upon as mental tools with which you are equipping yourselves for your future careers.

Because all your knowledge here gained is to serve you as tools, it must be acquired quantitatively rather than qualitatively. First, last, and all the

time, you are required to know not *how* simply, but how much, how far, how fast, to what extent, at what cost, with what certainty, and with what factor of safety. In a cultural education, where one is learning only to appreciate and to enjoy, it may satisfy the average mind to know that coal burned under a boiler generates steam which, entering a cylinder, moves a piston which turns the engine. But the engineer must know how many heat units there are in a pound of coal burned, how many of these are generated in the furnace, how many of them pass into the water, how much steam is consumed per horse power per hour, and, finally, how much effective work is done by the engine per pound of coal fed to the furnace. Merely qualitative knowledge leads to the grossest errors of judgment, and is of that kind of little learning which is a dangerous thing. At my summer home I have an hydraulic ram set below a dam, for furnishing a water supply. Nearby is an old abandoned water power grist mill. A man and his wife were looking at the ram last summer, and the lady was overheard to ask what it is for. The man looked about, saw the idle water-wheel of the old mill, and ventured the opinion that it must be used to run the mill. He knew a hydraulic ram when he saw it, and he knew that it is used to generate power, and that power will run a mill. *Ergo,* a hydraulic ram will run a mill. This conclusion is on a par with thousands of similar errors of judgment where one's knowledge is qualitative only. All engineering problems are purely quantita-

tive from the beginning to the end, and so are all other problems, whether material, or moral, or financial, or commercial, or social, or political, or religious. All judgments passed on such problems, therefore, must be quantitative judgments. How poorly prepared to pass such judgments are those whose knowledge is qualitative only! Success in all fields depends largely on the accuracy of one's judgment in foreseeing events, and in engineering it depends wholly on such accuracy. An engineer must see all around his problems, and take account of every contingency which can happen in the ordinary course of events. When all such contingencies have been foreseen and provided against, the unexpected cannot happen, as everything has been foreseen. It is customary to say that "the unexpected always happens." This, of course, is untrue. What is meant is that "it is only the unexpected which happens"; for the very good reason that what has been anticipated has been provided against.

In order that knowledge may be used as a tool in investigation and in the solution of problems, it must be so used constantly during the period of its acquisition. Hence the large amount of drawing-room, field, laboratory, and shop practice introduced into engineering courses. We try to make theory and practice go hand in hand. In fact, we teach that theory is only generalized practice. From the necessary facts, observed in special experiments, or in actual practice, general principles are deduced from which effects can be foreseen or derived for new

cases arising in practice. This is like saying, in surveying, that with a true and accurate hindsight an equally true and accurate forward course can be run. Nearly all engineering knowledge, outside the pure mathematics, is of this experimental or empirical character; and we generally know who made the experiments, how accordant his results were, and what weight can be given to his conclusions. When we can find in our engineering literature no sufficiently accurate data, or none exactly covering the case in hand, we must set to work to make experiments which will cover the given conditions, in order to obtain numerical factors, or possibly new laws, which will serve to make our calculations prove true in the completed structure or scheme. The ability to plan and carry out such crucial tests and experiments is one of the most important objects of an engineering college training, and we give our students a large amount of such laboratory practice.

In all such work it is the absolute truth we are seeking, and hence any guessing at data or falsifying of records or "doctoring" of the computations is of the nature of a professional crime. Any copying of records from other observers, when students are supposed to make their own observations, is both a fraud upon themselves as well as upon their instructor, and indicates a disposition of mind which has nothing in common with that of the engineer, who is always and everywhere a truth-seeker and truth-tester. The sooner such a person leaves the college of engineering, the better for him and for the

engineering profession. The mistakes of the engineer are quick to find him out and to proclaim aloud his incompetence. He is the one professional man who is obliged to be right, and for whom sophistry and self-deception are a fatal poison. But the engineer must be more than honest; he must be able to discern the truth. With him an honest motive is no justification. He must not only *believe* he is right; he must *know* he is right. And it is one of the greatest elements of satisfaction in this profession that it is commonly possible to secure in advance this almost absolute certainty of results. We deal with fixed laws and forces; and only so far as the materials used may be faulty, or of unknown character, or as contingencies can not be foreseen or anticipated, does a necessary ignorance enter into the problem.

It must not be understood, however, that with all of both the theory and practice we are able to give our students in their four or five years' course they will be full-fledged engineers when they leave us. They ought to be excellent material out of which, with a few years' actual practice, they may become engineers of the first order. Just as a young physician must have experience with patients, and as a young lawyer must have experience in the courts, so must a young engineer have experience with real problems before he can rightfully lay claim to the title of engineer. And in seeking this professional practice he must not be too choice. As a rule, the higher up one begins, the sooner his promotion

stops; and the lower down he begins, the higher will he ultimately climb. The man at the top should know in a practical way all the work over which he is called upon to preside, and this means beginning at the bottom. No position is too menial in the learning of a business. But as your college training has enabled you to learn a new thing rapidly, you should rapidly master minor details; and in a few years you should be far ahead of the ordinary apprentice who went to work from the grammar school or from the high school.

The great opportunity for the engineer of the future is in the direction and management of our manufacturing industries. We are about to become the world's workshop; as competition grows sharper, and as greater economies become necessary, the technically trained man will become an absolute necessity in the leading positions in all our industrial works. These are the positions hitherto held by men without technical training who have grown up with the business. They are being rapidly supplanted by technical men, who, however, must serve their apprenticeship from the bottom up.

In the foregoing description of the technical education and work of the engineer, the engineer himself has been considered as a kind of human tool to be used in the interest of society. His service to society alone has been in contemplation. But as the engineer has also a personality which is capable of appreciation and enjoyment of the best this world

has produced in the way of literature and art; as he is to be a citizen and a man of family; and, moreover, since he has a conscious self with which he must always commune, and from which he cannot escape, it is well worth his while to see to it that this self, this husband and father, this citizen and neighbor, is something more than a tool to be worked in other men's interests, and that his mind shall contain a library, a parlor, and a drawing-room, as well as a workshop. And yet how many engineers' minds are all shops out of which only shop talk can be drawn! Such men are little more than animated tools worked in the interest of society. They are liable to be something of a bore to their families and friends, almost a cipher in the social and religious life of the community, and a weariness of the flesh to their more liberal minded professional brethren. Their lives are a continuous grind, which has for them doubtless a certain grim satisfaction, but which is monotonous and tedious in comparison with what might have been. Even when valued by the low standard of money-making, they are not so likely to secure lucrative incomes as they would be with a greater breadth of information and worldly interest. They are likely to stop in snug professional berths which they find ready-made for them, under some sort of fixed administration, and maintain through life a subordinate relation to directing heads who, with a tithe of their technical ability, are yet able, with their worldly knowledge, their breadth of interests, and their fellowship with men, to dictate to

these narrower technical subordinates, and to fix for them their fields of operation.

In order, therefore, that the technical man, who in material things knows what to do, and how to do it, may be able to get the thing done, and to direct the doing of it, he must be an engineer of men and of capital as well as of the materials and forces of Nature. In other words, he must cultivate human interests, human learning, human associations, and avail himself of every opportunity to further these personal and business relations. If he can make himself as good a business man, or as good a manager of men, as he usually makes of himself in the field of engineering he has chosen, there is no place too great, and no salary too high for him to aspire to. Of such men are our greatest railroad presidents and general managers and the directors of our largest industrial establishments. While most of their special knowledge must also be acquired in actual practice, some of it can best be obtained in college. The one crying weakness of our engineering graduates is ignorance of the business, the social, and the political world, and of human interests in general. They have little knowledge in common with the graduates of our literary colleges, and hence often find little pleasure in such associations. They become clannish, run mostly with men of their profession, take little interest in the commercial or business departments of the establishments with which they are connected, and so become more and more fixed in their inanimate worlds of matter and

force. I beseech you, therefore, while yet students, to try to broaden your interests, to extend your horizons now into other fields, even but for a bird's-eye view, and to profit, as far as possible, by the atmosphere of universal knowledge which you can breathe here through the entire period of your college course. Try to find a chum who is in another department; go to literary societies; haunt the library; attend the available lectures in literature, science, and art; attend the meetings of the Science Club; and in every way possible, with a peep here and a word there, improve to the utmost these marvelous opportunities which will never come to you again.

For your own personal happiness, and that of your immediate associates, secure in some way, either in college or after leaving it, an acquaintance with some of the world's best literature, with the leading facts of history, and with the biographies of the greatest men in pure and applied science, as well as with those of statesmen and leaders in many fields. With this knowledge of great men, great thoughts, and great deeds will come that lively interest in men and affairs which is held by educated men generally, and which will put you on an even footing with them in your daily intercourse. This kind of knowledge also elevates and sweetens the intellectual life, leads to the formation of lofty ideals, helps one to a command of good English, and in a hundred ways refines and inspires to high and noble endeavor. This

is the cultural education leading to the appreciation and enjoyment man is assumed to possess.

Think not, however, that I depreciate the peculiar work of the engineering college. It is by this kind of education alone that America has already become supreme in nearly all lines of material advancement. I am only anxious that the men who have made these things possible shall reap their full share of the benefits.

In conclusion let me congratulate you on having selected courses of study which will bring you into the most intimate relation with the work of your generation. All life to-day is an endless round of scientific applications of means to ends, but such applications are still in their infancy. A decade now sees more material progress than a century in the past. Not to be scientifically trained in these matters is equivalent to-day to practical exclusion from all part and share in the industrial world. The entire direction of industry and commerce is to be in your hands. You are also charged with making the discoveries and inventions which will come in your generation. The day of the inventor, ignorant of science and of Nature's laws, has gone by. The mere mechanical contrivances have been pretty well exhausted. Henceforth profitable invention must include the use or embodiment of scientific principles with which the untrained artisan is unacquainted. More and more will invention be but the scientific

application of means to ends, and this is what we teach in the engineering schools. Already our patent office is much puzzled to distinguish between engineering and invention. Since engineering proper consists of the solution of new problems in the material world, and since invention is likewise the discovery of new ways of doing things, they cover the same field. But an invention is patentable, while an engineering solution is not. Invention is supposed in law to be an inborn faculty by which new truth is conceived by no definable way of approach. If it had not been reached by a particular individual, it is assumed that it might never have been known. An engineering solution is supposed, and rightly, to have been reached by logical processes through known laws of matter, and force, and motion, so that another engineer, given the same problem, would probably have reached the same or an equivalent result. And this is not patentable. Already a very large proportion of the patents issued could be nullified on this ground if the attorneys only knew enough to make their case. More and more, therefore, are the men of your profession to be charged with the responsibility, and to be credited with the honor, of the world's progress, and more and more is the world's work to be placed under your direction. These are your responsibilities and your honors. The tasks are great, and great will be your rewards. That you may fitly prepare yourself for them is the hope and trust of your teachers in this college of engineering.

I will close this address by quoting Professor

Huxley's definition of a liberal education. Says Huxley: "That man, I think, has had a liberal education who has been so trained in youth that his body is the ready servant of his will, and does with ease and pleasure all the work that, as a mechanism, it is capable of; whose intellect is a clear, cold, logic engine, with all its parts of equal strength, and in smooth working order; ready, like a steam engine, to be turned to any kind of work, and spin the gossamers as well as forge the anchors of the mind; whose mind is stored with a knowledge of the great and fundamental truths of Nature and of the laws of her operations; one who, no stunted ascetic, is full of life and fire, but whose passions are trained to come to heel by a vigorous will, the servant of a tender conscience; who has learned to love all beauty, whether of Nature or of art, to hate all vileness, and to respect others as himself.

"Such a one and no other, I conceive, has had a liberal education; for he is, as completely as a man can be, in harmony with Nature. He will make the best of her, and she of him. They will get on together rarely; she as his ever beneficent mother; he as her mouthpiece, her conscious self, her minister and interpreter."

THE BASES OF ENGINEERING EDUCATION—LANGUAGE

V

THE VALUE OF ENGLISH TO THE TECHNICAL MAN

JOHN LYLE HARRINGTON

[AMONG engineers there is increasing recognition of the importance of English in engineering practice. In connection with the following essay, Dr. Waddell and Mr. Harrington, the editors of *Engineering Addresses,* remark that "Upon whether its teachings be followed or ignored may depend the success or failure of any technical student to attain in after life the highest rank in the engineering profession. Possessing a mastery of the English language, he may or may not rise to eminence; but without it he certainly cannot. Any engineering student who wilfully neglects the study of his own language deserves the failure to attain eminence which assuredly will be his fate." The author, John Lyle Harrington (1868–   ), a graduate of the University of Kansas and of McGill University, is a distinguished engineer. As a member of the Elmira Bridge Company, of the Keystone Bridge Works, and of the Berlin Iron Bridges Company, he designed many of the heavy bridges of the continent. For some time also he was Chief Engineer and Manager of the Locomotive and Machine Company of Montreal. At present he is a member of the firm of Harrington, Howard, and Ash. His essay, which first appeared in pamphlet form, is reprinted, by permission of the publishers, from *Engineering Addresses.*]

Language is an instrument, a medium for the exchange of thought. If, in individual instances, both speaker and hearer employ words in the same sense, and arrange them in the same manner, the expressed ideas will be perfectly understood, whether the language be in accordance with good usage or not. But if thought is to be conveyed without loss to a larger audience, the medium must be substantially perfect. Words must not only be used in accordance with their accustomed and generally accepted meanings, and with all the shades and niceties of those meanings, but they must also be arranged in accordance with the accepted construction of phrase, clause, and sentence; and the whole argument must be so ordered with regard to the sequence and the relations of the various ideas that the hearer shall be compelled to understand. Discourses in which thoughts, though they be ever so clearly expressed, are not arranged in logical order, will fail in their purpose, because the argument is confused, and the mind of the hearer is occupied with the language instead of the substance of the thought. You will recall Sam Weller's remark regarding Mr. Nupkins' eloquence that "his ideas come out so fast they knock each other's heads off and you can't tell what he is driving at." Like any other instrument, the value of language is in direct proportion to our knowledge of it and our skill in its use. If we understand it fully, and use it skillfully, it will serve our purpose well; but if we are novices and bunglers, only disappointment will result.

Language, though it will not supply the place of thought, is a most essential instrument to every man. To him who is without important thought to express it is not a very valuable tool. The laborer does not require it in handling the pick and shovel; it is only in his social relations that he has much need for speech. It is not important that the stoker speak fluently, or that the mechanic be an able orator or writer. But as we proceed from the lower to the higher and more intellectual occupations, the need and the value of knowledge and command of language rapidly increase. The politician, we sometimes think, makes skillful use of language to hide his thought or to dissemble. Indeed, in all walks of life there are times when words are well employed to obscure the thought. But the physician must be skillful in the use of language in order to direct and control his patients, as well as to write, and to understand the writings of his fellow physicians. The clergyman needs it to please, to inform, to convince, and to persuade his auditors. The technical man—that is, the engineer, the architect, and the applied scientist of every kind—finds a sound, accurate knowledge of the language essential to him in every part of his work. A wide and precise knowledge of words is required in his reading as well as in his general writing; in his business and professional conversations even more than in those of a social nature. In the preparation and interpretation of technical correspondence, specifications, and contracts, the use of perfect language reaches the highest degree

of importance. The lawyer alone needs to be so much of a precisian, and he attains that end by very awkward and cumbersome means.

The technical man of the highest order is not only a cultured gentleman, versed in all the amenities of polite society, familiar with the best literature in his own language and probably in that of one or two others, able to read many branches of learning understandingly and to discuss them intelligently; but, in addition, he has special knowledge of mathematics and the applied sciences, and he is able not only to understand what is written or spoken about them but also to express his own thought readily, accurately, and logically. The successful technical man, it has been well said, must know much about everything and everything about something, but his ideas and knowledge are of small value except in so far as he can convey them to others; for, since he does not often labor with his hands, he must instruct and direct those who do. Thus, language is his most important tool, and it certainly behooves him to see that it is always in good order. His reputation as a gentleman and as a professional man depends very largely upon his knowledge and use of English.

Technical men are peculiarly prone to offend in the use of their mother tongue because they have not, as a rule, read deeply in literature nor studied the construction of the language. The technical man who has a thorough knowledge of English has had

the wisdom and patience to supplement his technical education by an arts course, has read widely, or possesses the gift of speech. Long-continued and intimate association with those who employ excellent English will ensure reasonably good usage. In fact, such association is almost essential, no matter what the education may be; but the knowledge of the language so acquired generally breaks down when it is applied to technical matters in which extreme accuracy is a requisite, and in which the terms differ much from those used in ordinary conversation. There is no royal road to a knowledge of English.

Some of our better universities are now offering a six years' course which combines the usual arts and technical courses, each of which ordinarily occupies four years, but which have many subjects in common. This is a decided step in the right direction; for technical men generally are coming into a more complete realization of their deficiencies, and are insisting that young technists be more liberally educated. The professional man does not always remain a technist; in fact, he frequently becomes a man of affairs as well, where a liberal education is even more essential than in his purely technical work.

Before passing to a consideration of the specific advantages enjoyed by the technical man who uses good English, let us glance at some of the grosser faults of which so many are guilty; for there is no better way to attain a comprehension of the good than by contrasting it with the bad. It has been well

said that it is no virtue to speak good English, but that it is a disgrace to use bad English.

You will say that it is absurd to state that men who have graduated from college cannot spell correctly, but many of them cannot. *S-e-d,* said; *p-e-a-r,* pier, are extreme but true examples. It is common to find misspelled words in letters written by young engineers. They consider such errors of no material consequence because they are not technical errors. The mind has been so fixed upon the scientific work during the course of study, and while the early experience is being acquired, that such matters as language and culture seem to be of little importance. But the recipient of the letter generally takes a different view of the matter; for he justly considers the writer something of an ignoramus.

Errors of spelling and punctuation are both due to unpardonable carelessness and ignorance; for any one can learn to spell and to punctuate correctly, and no man should be given a degree or a diploma by any institution of learning unless he does so habitually.

Grossly bad grammar is also common. It generally arises from carelessness in ordering the thought and speech rather than from lack of knowledge of correct usage, but it is frequently attributed to ignorance; and certainly the penalty is not too severe. In many instances, however, ignorance is the true cause of the error. The study of grammar commonly ceases when the student leaves the graded schools. Thereafter he assumes that his knowl-

edge of the subject is full and complete, and that he need give it no further attention, notwithstanding the fact that his capacity for thought and the need of means for its expression continue to increase. His vocabulary grows; but his knowledge of the fundamental principles which govern its use not only does not expand as his needs require, but it is allowed to become uncertain and to diminish through lack of exercise. When the matter is thought of at all, it is assumed that in some vague, uncertain way habit will serve instead of knowledge and understanding. The grammar is put away like other childish things.

But the highest skill in the use of language is not attained when our words are properly spelled or pronounced and our sentences formed in accordance with the rules of grammar. In fact, these are only bare and absolute essentials, the skeleton of our language, which must still be provided with flesh and blood and nerves before it will live and fulfill its mission. The whole purpose for which language is employed is to impress our thought upon others in such a way that they shall feel or think or act as we desire. To attain this end it is essential that we make intelligent use of the arts of rhetoric and oratory, that we know the laws of composition, the methods of ordering and constructing our discourse so that it will lead the minds of our hearers wherever we wish, and not only convey our thought but also induce our auditors to think along the lines that will benefit our purpose.

It is deplorably rare to find young technical men

in possession of an intimate knowledge of rhetoric. Business correspondence is often annoyingly protracted because one or both of the parties conducting it ignores the simple law of unity, and fails to round out and complete the subject under discussion. Gross errors of composition are quite as frequent in the correspondence of the technically educated man as they are in that of the ordinary clerk who went to work when he left the grammar school. It is because engineers are so little accustomed to order their thought and language properly that they have so little part in the business and correspondence of the corporations which employ them. It is notorious that a technist is rarely a good business man. This is partly because of the exaggerated importance he gives to technical matters, but very largely because his thought is clumsily expressed and awkwardly ordered.

The character of the technical man's language is important in his social and business intercourse; in his business and professional correspondence; in the promulgation of orders, rules, and regulations for the guidance of those under his direction; in the preparation of specifications, contracts, and reports; in writing and delivering addresses and technical papers; and in writing technical books for the advancement of his profession.

In conversation, earnestness and force may, in some measure, counteract the evil influence of bad English; but since less care is commonly given to the

spoken word than to the written, the results of bad habits of speech are much the same in either case; and in moments of special interest or excitement the habitual language is employed. Speech is usually heard but once; therefore its errors are much more likely to pass unnoticed than those which are written and may be read repeatedly; and the audience of the speaker is much more limited than that of the writer; therefore it would seem less important to speak correctly than to write correctly. But it must not be forgotten that in conversation there is no time, as a rule, to give thought to the form of speech and that all the errors one is accustomed to make are likely to occur. The habit of using good English should be so firmly fixed that one is not conscious of it.

A technical man is, presumably, an educated man; and if he does not speak like one, suspicion is cast upon the entire range of his learning. When a man cannot spell correctly, nor use ordinarily good grammar (and there are many university men who cannot), it is difficult to convince others that he is professionally able. The great majority of technical men occupy positions in the organizations of railways, governments, constructing companies, and manufacturing corporations. These positions are obtained by means of acquaintances made in a social way, by interview, by correspondence, or on account of an earned reputation. Yet I have granted interviews to many technical men who spoke like common laborers, and have received hundreds of letters from

them that would be a disgrace to a grammar school student. There are technically educated men who say, "I have saw," "I seen," and "I done"; and there are men in high places who require no further proof of the speaker's ignorance, not only of English, but of technical matters as well. One who is thus ignorant of the language finds social progress substantially impossible. This may seem a trivial matter and foreign to our purpose, but it is not. Matters of very large importance are often settled by favor, and favor frequently follows social position. Other things being equal, almost any one will show his friend the preference in business or professional matters. It is even common to stretch a point in favor of a friend.

Language has large weight in classifying a man, infinitely more than manner or dress. It exhibits his breeding and indicates his social status. I do not mean that it shows whether he belongs to the so-called "Smart Set," but whether he is of the educated, cultured class, whether you would care to entertain him at all, and, if so, whether you would send him to your club, or whether you may extend the extreme courtesy of inviting him to your home. This may appear at first glance to be of small consequence; but great things often result from associations quickly formed. In fact, such social relations make largely for success or failure in the business or professional world. Many have received the opportunity which led to eminence through the

recommendation of a casual acquaintance who was favorably impressed.

There are many vocations in which it is not essential that a man be cultured and intelligent; but the technical professions are not among them. Nothing so surely marks a man's secret habits of thought, his real character, as the little tricks of speech which are exhibited when his mind is upon the matter rather than the manner of his speech. If his thought be habitually coarse, crude, or brutal, his speech will make the fact manifest at times; and the speech of a moment frequently produces a permanent and vital effect.

In business correspondence the value of good usage is still more manifest than in conversation. A letter very probably passes through many hands and multiplies the good or bad impressions of the writer it produces. If its import is not clear, it may cause disagreement or involve the writer in a serious financial disadvantage. Even bad punctuation will often seriously alter the entire meaning of a sentence, and particularly bad grammar at once stamps the writer as an ignoramus. The art of letter writing, like a knowledge of grammar, is commonly considered to be within the range of everyone's learning and skill; but anyone who has had large experience in business correspondence knows that few men write good letters. It is so rare to find a matter which is composed of more than one or two items clearly, concisely, and thoroughly discussed in a letter that

favorable attention is immediately attracted to its writer. Not a few men owe the opportunity for advancement to their ability to write a good letter. Even though one be thoroughly versed in his subject, and his discourse be well worth the time and attention of men of affairs, bad grammar will cast such suspicion over his whole equipment of learning that his argument will often be put aside without substantial consideration. Bad grammar is not a bar to the acquisition of money, but it substantially prohibits attainment to high position in the scientific world.

The detrimental results of bad English in conversation or in correspondence are by no means so certain as in more formal technical papers. In the preparation of articles for the technical press, and papers for the learned societies, there is time to study form and style and to eliminate errors due to haste; hence, when such matters are ill-written, it is not unfairly argued that the writer is ignorant of the correct use of the language. Such an opinion, widely disseminated, as it is likely to be when it originates thus, is exceedingly detrimental to the writer. It weakens his arguments, causes him to be misunderstood, or so detracts from the interest of his readers that the matter is not read. The idea that a technical paper is dry at best, and that the English employed in it is of small consequence, has long been proved incorrect. There is so much nowadays that is well written that no busy professional man is will-

ing to spare the extra time and effort necessary to read and digest an ill-written paper.

A merchant may advertise his wares, a manufacturer his product, but reasonable modesty and his code of ethics prevent a professional man from advertising his skill. If he does not become known by his work or his writings, he remains in comparative obscurity. His ability is clearly exposed in his writings, in which he gives to the profession his best thought; but if he cannot write easily and well, he will probably not write at all; for the censorship of the learned societies is now severe, and is rapidly growing more so. Every successful technical man desires to leave a permanent record of the results of his best thought and work to aid his co-workers and successors. An ably written description of work performed, discoveries made, or methods developed accomplishes more for the advancement of science than many well designed and well executed constructions. The latter benefit those who see them; the former may help all who can read.

Provoking and expensive errors often arise from the misunderstanding of badly expressed orders, rules, and regulations. In large corporations, especially in railway, contracting, and engineering companies, where employees are distributed over a wide area, it is impossible for an officer to give individual instructions, or to see personally that they are carried out; hence, general instructions must be so clear that they cannot be misunderstood or evaded. It is

hardly necessary to say that the consequences of a mistake in train orders, in instructions regarding breaking track for repairs or renewals, or for making temporary construction to span washouts, may result in expensive and fatal accidents. And even minor errors, oft repeated, may prove very costly.

But the preparation of reports, specifications, and contracts is the most particular and momentous task the technical man has to perform. A misused word, a phrase whose meaning is ambiguous, a paragraph that is confused, or the omission of a direction or a precaution, may result in great damage to both the client and the technical man. It is not enough to be careful in a general way. Every word, every phrase, every sentence, has a direct and vital bearing on the work governed by the documents. I have known the presence in a contract of a single word of equivocal meaning to cost one of the parties many thousands of dollars, though when the contract was drawn there was no question regarding the intent of the parties to it. Probably the majority of the civil law suits are caused not by trickery, nor deceit, nor dishonesty, but by the use of ambiguous words and phrases, bad ordering of the matter, incompleteness, and other faults in the language of the correspondence, specifications, and contracts. There is no more certain way for the engineer to protect his own and his client's interests than to prepare all documents in accordance with the best English usage as well as with technical skill; and there is no surer

way to lay the foundation for trouble and financial loss than to neglect the character of his language.

Notwithstanding the vital importance of clear, concise, and full expression in such documents, it is not uncommon to find specifications and contracts so bad in their construction that they fail utterly in their purpose. Let me quote an illustration from the specifications, prepared by an architectural firm of some repute, for the construction of a building which cost nearly one hundred thousand dollars:

"Material and Workmanship. The entire frame work, columns, beams, etc., as indicated by the framing plans, or as specified, is to be of wrought steel, of quality hereinafter designated, all materials to be provided and put in place by the contractor. All work to be done in a neat and skillful manner, and is to guarantee the construction and workmanship with a bond equal to amount of tender for a term of five years, satisfactory to the proprietor and architects, to properly carry or support the loads it is designated to carry, namely its own weight, the weight of the several floors, roof and walls resting thereon, a 10,000 gravity tank, and the pressure of any wind which may not be designated a hurricane, and future three stories. The floor beams are to be calculated for a maximum load of 150 pounds to the square foot (using *C* type IV of the Clinton Fire-proof system, of Clinton, Mass.). The columns are to be calculated for a vertical load above mentioned and for horizontals and wind pressure

and snow pressure, also roof. The whole to be calculated heavy enough for three additional stories on building should they be put on at any time, with connections at top columns to receive future columns. The columns on ground floor supporting front to be calculated in same proportion with all the rods necessary where shown. The whole of the columns to be one size throughout, those that carry more weight reinforced, and all columns to be kept as small as possible in proper construction. Each column to have ⅜-inch holes bored or punched every 4 ft. 6 in. in height on each corner (for use of other trades to fasten metal lath)."

The building was constructed under these specifications, not according to them; that would be impossible. But it is hardly necessary to say that the proprietors were not safeguarded. The wretched paragraph quoted is no worse than a contractor finds in specifications almost every day; for it is composed, as a large number of engineers and architects compose their specifications, by copying and combining sentences or paragraphs from various sources instead of by writing them from knowledge of the construction desired. In such instances the client is protected more by the honesty, knowledge, and skill of the contractor than by those of the architect.

The lawyers and the courts are kept busy rectifying the blunders of other professional men who do ill what they are paid to do well. I know of one contractor, grown gray in the business of constructing buildings, who has never completed a contract

without a lawsuit, and who has never lost a lawsuit. This fact speaks ill for the architects under whom he worked, yet they are probably no worse than their fellows. If it were not good policy to be reasonably honest, many another contractor might easily approach his record.

It would appear that we have given more attention to bad than to good English. This method is not illogical; for, manifestly, if the bad be eliminated, the good will remain; and if the evils arising from the abuse of the language be fully comprehended, there will be serious endeavor to improve the usage. The laws of the language are commonly violated from mere carelessness. Slang and provincialisms creep in, and destroy its force and elegance; the expression becomes slovenly and the thought obscure; and what constitutes good English is forgotten.

Language itself is merely an instrument. The sole service English can render is to convey the speaker's thought and purpose fully and accurately to the minds of his auditors. But this service alone will amply repay years of study and a life of care in and attention to the use of the English language.

VI

ART AND SCIENCE

HERBERT SPENCER

[ALTHOUGH Mr. Harrington regards the study of English from a utilitarian point of view, he does not overlook its cultural aspects. Language, indeed, is one of the portals leading to the realm of art! The fact that literature, like sculpture, painting, and music, is closely related to science is, however, not always appreciated. For this reason the following passage, extracted from *Education* (1861), published by D. Appleton and Company, possesses a perennial freshness. The author, Herbert Spencer (1820–1903), was largely self-educated. Beginning his career as an engineer at the age of seventeen, he spent ten years on the railways of Great Britain. Later he served on the staff of the *Economist*. Finally he undertook the development of a system of philosophy intended to embrace the whole range of knowledge. Of the volumes connected with this enterprise, *First Principles* (1862) is most generally known. It provides an excellent introduction to one of the significant figures in the thought of the nineteenth century.]

And now we come to that remaining division of human life which includes the relaxations, pleasures, and amusements filling leisure hours . . . the enjoyments of Nature, of literature, and of the fine arts, in all their forms. . . . Bringing everything, as we have, to the test of actual value, it will perhaps be

inferred that we are inclined to slight these less essential things. No greater mistake could be made, however. We yield to none in the value we attach to æsthetic culture and its pleasures. Without painting, sculpture, music, poetry, and the emotions produced by natural beauty of every kind, life would lose half its charm. So far from thinking that the training and gratification of the tastes are unimportant, we believe the time will come when they will occupy a much larger share of human life than now. When the forces of Nature have been fully conquered to man's use—when the means of production have been brought to perfection—when labor has been economized to the highest degree—when education has been so systematized that a preparation for the more essential activities may be made with comparative rapidity—and when, consequently, there is a great increase of spare time, then will the poetry, both of Art and Nature, rightly fill a large space in the minds of all.

Recognizing thus the true position of æsthetics . . . we have now to inquire what knowledge is of most use to this end,—what knowledge best fits for this remaining sphere of activity. To this question the answer is still the same as heretofore. Unexpected as the assertion may be, it is nevertheless true that the highest art of every kind is based upon science,—that without science there can be neither perfect production nor full appreciation. Science, in that limited technical acceptation current in society, may not have been possessed by many artists

of high repute; but acute observers as they have been, they have always possessed a stock of those empirical generalizations which constitute science in its lowest phase; and they have habitually fallen below perfection, partly because their generalizations were comparatively few and inaccurate. That science necessarily underlies the fine arts becomes manifest, *à priori,* when we remember that art products are all more or less representative of objective or subjective phenomena; that they can be true only in proportion as they conform to the laws of these phenomena; and that before they can thus conform the artist must know what these laws are. That this *à priori* conclusion tallies with experience we shall soon see.

Youths preparing for the practice of sculpture have to acquaint themselves with the bones and muscles of the human frame in their distribution, attachments, and movements. This is a portion of science; and it has been found needful to impart it for the prevention of the many errors which sculptors who do not possess it commit. For the prevention of other mistakes, a knowledge of mechanical principles is requisite; and such knowledge not being usually possessed, grave mechanical mistakes are frequently made. Take an instance. For the stability of a figure it is needful that the perpendicular from the center of gravity—"the line of direction," as it is called—should fall within the base of support; and hence it happens that when a man assumes the attitude known as "standing at ease," in which

one leg is straightened and the other relaxed, the line of direction falls within the foot of the straightened leg. But sculptors unfamiliar with the theory of equilibrium not uncommonly so represent this attitude that the line of direction falls midway between the feet. Ignorance of the laws of momentum leads to analogous errors: as witness the admired Discobolus, which, as it is posed, must inevitably fall forward the moment the quoit is delivered.

In painting, the necessity for scientific knowledge, empirical if not rational, is still more conspicuous. In what consists the grotesqueness of Chinese pictures, unless in their utter disregard of the laws of appearances,—in their absurd linear perspective, and their want of aërial perspective? In what are the drawings of a child so faulty, if not in a similar absence of truth,—an absence arising, in great part, from ignorance of the way in which the aspects of things vary with the conditions? Do but remember the books and lectures by which students are instructed; or consider the criticisms of Ruskin; or look at the doings of the Pre-Raphaelites,—and you will see that progress in painting implies increasing knowledge of how effects in Nature are produced. The most diligent observation, if not aided by science, fails to preserve from error. Every painter will indorse the assertion that unless it is known what appearances must exist under given circumstances, they often will not be perceived; and to know what appearances must exist is, in so far, to understand the science of appearances. From want of science

Mr. J. Lewis, careful painter as he is, casts the shadow of a lattice window in sharply defined lines upon an opposite wall; which he would not have done had he been familiar with the phenomena of penumbræ. From want of science, Mr. Rossetti, catching sight of a peculiar iridescence displayed by certain hairy surfaces under particular lights (an iridescence caused by the diffraction of light in passing the hairs), commits the error of showing this iridescence on surfaces and in positions where it could not occur.

To say that music, too, has need of scientific aid will seem still more surprising. Yet it is demonstrable that music is but an idealization of the natural language of emotion; and that, consequently, music must be good or bad according as it conforms to the laws of this natural language. The various inflections of voice which accompany feelings of different kinds and intensities have been shown to be the germs out of which music is developed. It has been further shown that these inflections and cadences are not accidental or arbitrary, but that they are determined by certain general principles of vital action, and that their expressiveness depends on this. Whence it follows that musical phrases and the melodies built on them can be effective only when they are in harmony with these general principles. It is difficult here properly to illustrate this position. But perhaps it will suffice to instance the swarms of worthless ballads that invest drawing-rooms, as compositions which science would forbid. They sin

against science by setting to music ideas that are not emotional enough to prompt musical expression and they also sin against science by using musical phrases that have no natural relation to the ideas expressed, even where these are emotional. They are bad because they are untrue. And to say they are untrue is to say they are unscientific.

Even in poetry the same thing holds. Like music, poetry has its root in those natural modes of expression which accompany deep feeling. Its rhythm, its strong and numerous metaphors, its hyperboles, its violent inversions, are simply exaggerations of the traits of excited speech. To be good, therefore, poetry must pay respect to those laws of nervous action which excited speech obeys. In intensifying and combining the traits of excited speech, it must have due regard to proportion.—must not use its appliances without restriction but, where the ideas are least emotional, must use the forms of poetical expression sparingly; must use them more freely as the emotion rises; and must carry them all to their greatest extent only where the emotion reaches a climax. The entire contravention of these principles results in bombast or doggerel. The insufficient respect for them is seen in didactic poetry. And it is because they are rarely fully obeyed that we have so much poetry that is inartistic.

Not only is it that the artist, of whatever kind, cannot produce a truthful work unless he understands the laws of the phenomena he represents; but it is that he must also understand how the minds of

spectators or listeners will be affected by the several peculiarities of his work,—a question in psychology. What impression any given art product generates manifestly depends upon the mental natures of those to whom it is presented; and as all mental natures have certain general principles in common, there must result certain corresponding general principles on which alone art products can be successfully framed. These general principles cannot be fully understood and applied unless the artist sees how they follow from the laws of mind. To ask whether the composition of a picture is good is really to ask how the perceptions and feelings of observers will be affected by it. To ask whether a drama is well constructed is to ask whether its situations are so arranged as duly to consult the power of attention of an audience, and duly to avoid overtaxing any one class of feelings. Equally in arranging the leading divisions of a poem or fiction, and in combining the words of a single sentence, the goodness of the effect depends upon the skill with which the mental energies and susceptibilities of the reader are economized. Every artist, in the course of his education and after-life, accumulates a stock of maxims by which his practice is regulated. Trace such maxims to their roots, and you find they inevitably lead you down to psychological principles. And only when the artist rationally understands these psychological principles and their various corollaries, can he work in harmony with them.

We do not for a moment believe that science will

make an artist. While we contend that the leading laws both of objective and subjective phenomena must be understood by him, we by no means contend that knowledge of such laws will serve in place of natural perception. Not only the poet, but also the artist of every type, is born, not made. What we assert is that innate faculty alone will not suffice, but must have the aid of organized knowledge. Intuition will do much, but it will not do all. Only when genius is married to science can the highest results be produced.

As we have above asserted, science is necessary not only for the most successful production but also for the full appreciation of the fine arts. In what consists the greater ability of a man than of a child to perceive the beauties of a picture, unless it is in his more extended knowledge of those truths in Nature or life which the picture renders? How happens the cultivated gentleman to enjoy a fine poem so much more than a boor if it is not because his wider acquaintance with objects and actions enables him to see in the poem much that the boor cannot see? And if, as is here so obvious, there must be some familiarity with the things represented before the representation can be appreciated, then the presentation can be completely appreciated only in proportion as the things represented are completely understood. The fact is, that every additional truth which a work of art expresses gives an additional pleasure to the percipient mind,—a pleasure that is missed by those ignorant of this truth.

The more realities an artist indicates in any given amount of work, the more faculties does he appeal to; the more numerous associated ideas does he suggest; the more gratification does he afford. But to receive this gratification the spectator, listener, or reader, must know the realities which the artist has indicated; and to know these realities is to know so much science.

And now let us not overlook the further great fact, that not only does science underlie sculpture, painting, music, poetry, but that science is itself poetic. The current opinion that science and poetry are opposed is a delusion. It is doubtless true that as states of consciousness, cognition and emotion tend to exclude each other. And it is doubtless also true that an extreme activity of the reflective powers tends to deaden the feelings, while an extreme activity of the feelings tends to deaden the reflective powers; in which sense, indeed, all orders of activity are antagonistic to each other. But it is not true that the facts of science are unpoetical, or that the cultivation of science is necessarily unfriendly to the exercise of imagination or the love of the beautiful. On the contrary science opens up realms of poetry where to the unscientific all is a blank. Those engaged in scientific researches constantly show us that they realize not less vividly, but more vividly, than others, the poetry of their subjects. Whoever will dip into Hugh Miller's works on geology, or read Mr. Lewes' *Seaside Studies,* will perceive that science excites poetry rather than extinguishes it. And who-

ever will contemplate the life of Goethe will see that the poet and the man of science can co-exist in equal activity. Is it not, indeed, an absurd and almost a sacrilegious belief that the more a man studies Nature the less he reveres it? Think you that a drop of water, which to the vulgar eye is but a drop of water, loses anything in the eye of the physicist who knows that its elements are held together by a force which, if suddenly liberated, would produce a flash of lightning? Think you that what is carelessly looked upon by the uninitiated as a mere snow flake does not suggest higher associations to one who has seen through a microscope the wondrously varied and elegant forms of snow crystals? Think you that the rounded rock marked with parallel scratches calls up as much poetry in an ignorant mind as in the mind of a geologist, who knows that over this rock a glacier slid a million years ago? The truth is, that those who have never entered upon scientific pursuits know not a tithe of the poetry by which they are surrounded. Whoever has not in youth collected plants and insects knows not half the halo of interest which lanes and hedge-rows can assume. Whoever has not sought for fossils has little idea of the poetical associations that surround the places where imbedded treasures were found. Whoever at the seaside has not had a microscope and aquarium has yet to learn what the highest pleasures of the seaside are. . . .

We find, then, that even for this remaining division of human activities, scientific culture is the

proper preparation. We find that æsthetics in general are necessarily based upon scientific principles and can be pursued with complete success only through an acquaintance with these principles. We find that for the criticism and due appreciation of works of arts, a knowledge of the constitution of things, or, in other words, a knowledge of science, is requisite. And we not only find that science is the handmaid to all forms of art and poetry but that, rightly regarded, science is itself poetic.

MATHEMATICS

VII

THE PLACE OF MATHEMATICS IN ENGINEERING PRACTICE

SIR WILLIAM HENRY WHITE

[THROUGH scholarship and practice Sir William Henry White (1845–1913) was admirably qualified to discuss the relations between mathematics and engineering. As a professor in the Royal School of Naval Architecture and the Royal Naval College, he helped to shape recent theories of marine construction. As an engineer, however, his influence was even more notable. While head of the shipbuilding department of Armstrong, Mitchell, and Company he designed the *Takachiho* for Japan and the *Charleston* for the United States, introducing many improvements over the older cruiser types. On becoming Director of Naval Construction, a position which he occupied for seventeen years, he developed the battleship types which were standard in most navies during the last twenty years of his life. Nor were his activities limited to men-of-war; for it was largely through his efforts that turbines were adopted on large passenger ships. Among the 250 vessels which he designed and constructed is the giant *Mauretania*. Sir William was not only a teacher and a practitioner, but also the author of several valuable monographs. The following address, delivered before the Fifth International Congress of Mathematicians, is reprinted, by permission of the editor, from *Nature*, September 19, 1912.]

The foundations of modern engineering have been laid on mathematics and physical science; the

practice of engineering is now governed by scientific methods applied to the analysis of experience and the results of experimental research. Engineering has been defined as "the art of directing the great sources of power in Nature for the use and convenience of man." An adequate acquaintance with the laws of Nature and obedience to those laws are essential to the full utilization of these sources of power. It is now universally recognized that the educated engineer must possess a knowledge of the sciences which bear upon his professional duties as well as thorough practical training and experience in actual engineering work. Of these sciences the mathematical is undoubtedly of the greatest importance. The range and character of mathematical knowledge which can be considered adequate are gradually being agreed upon as experience is enlarged; and present ideas are embodied in the courses of study prescribed in the calendars of schools of engineering.

The preponderance of opinion amongst engineers now favors the teaching of science in general, and of mathematics in particular, on lines which will ensure greater breadth of view and fuller capability for dealing with new problems arising in professional work. Whatever branch of engineering a man may select for his individual practice, he must have a fundamental knowledge of mathematics; and in some branches, in order to do his work well, he will have to add considerably to the mathematical knowledge which is sufficient for a degree.

As time passes, the mathematician and the practicing engineer have come to understand each other better, and to be mutually helpful. While engineers as a class cannot claim to have made many important or original contributions to mathematical science, some men trained as engineers have done notable work of a mathematical character. The names of Rankine, William Froude, and John Hopkinson, among British engineers, hold an honored place in mathematics. Mathematicians of eminence have spent their lives in the tuition of engineers, and in that way have greatly influenced the practice of engineering; but while they have necessarily become familiar with the problems of engineering as a consequence of their connection with it, they have not accomplished much actual engineering work, and none of it has been of first importance. There is an abiding distinction between mathematicians and engineers. Mathematicians regard engineering chiefly from the scientific point of view, and are primarily concerned with the bearing of mathematics on engineering practice, the construction of theories, and the framing of useful rules. Engineers, even when well equipped with mathematical knowledge, are primarily devoted to the design and construction of efficient and durable works, their main object being to secure the best possible association of efficiency and economy, and so to achieve practical and commercial success. There is evidently room for both classes; and their collaboration in modern times has produced wonderful results.

The proper use of mathematics in engineering practice is now generally agreed to include the development of a mathematical theory based on assumptions which are thought to embody and to represent conditions disclosed by past practice and observation. Frequently these theoretical investigations give rise to valuable suggestions for further observation or experimental investigations. Useful rules are also devised, in many instances. . . . Formerly it was thought by men of science that purely mathematical investigation and reasoning would do all that is required for the guidance of engineering practice. It is now admitted that such investigations will not suffice, and that the chief services which can be rendered to engineering by mathematicians consist in the suggestion of the best directions and methods for experimental research, the conduct of observations on the behavior of existing works, the establishment of general principles based on analysis of experience, and the framing of practical rules embodying scientific principles.

The contrast between present and past methods can be illustrated by comparing investigations made during the eighteenth century into the behavior of ships amongst waves by Daniel Bernoulli, who won the prize offered by the Royal French Academy of Science in 1757, and work done by William Froude a century later in connection with the same subjects. Bernoulli was the greater mathematician, but had only a small knowledge of the sea and of ships. His memoir was a mathematical treatise; his practical

rules, although deduced from mathematical investigations which were themselves correct, depended upon certain fundamental assumptions which did not correctly represent either the phenomena of wave motion or the causes producing and limiting the rolling oscillations of ships. Bernoulli realized and dwelt upon the need for further experiment and observation, and showed remarkable insight into what was needed; but the fact remains that he neither made such experiments himself nor was able to induce others to make them. As a consequence his practical rules for the guidance of naval architects were incorrect, and would have produced mischievous results if they had been applied in practice.

William Froude was a trained engineer who had a good knowledge of mathematics and a mathematical mind. His acquaintance with the sea and ships was considerable; his skill as an experimentalist was remarkable, and he was fortunate enough to secure the support of the Admiralty through the Constructive Department. He thus obtained the services of the officers of the Royal Navy in making a long series of accurate and detailed observations on the characteristic features of ocean waves as well as on the rolling of ships amongst them. In this way, starting with the formulation of a mathematical theory of wave motion, Froude added corrections based on experimental research, and succeeded eventually in devising methods by means of which naval architects can make close approximations to the probable behavior of ships of new design. In these

approximations allowance can be made for the effect of water resistance to the rolling motion,—a most important factor in the problem which could not be dealt with until experimental research had been made, and results had been subjected to mathematical analysis. In addition, Froude laid down certain practical rules for the guidance of naval architects, and the application of these rules has been shown by long experience to favor the steadiness—that is, the comparative freedom from rolling—of ships designed in accordance with them. In short, a problem which had proved too difficult when attacked by Daniel Bernoulli in purely mathematical fashion was solved a century later by Froude, who employed a combination of mathematical treatment and experimental research.

Another example of the contrast between earlier and present methods is to be found in the treatment of the resistance offered by water to the onward motion of ships. At an early date mathematicians were attracted to this subject, and many attempts were made to frame mathematical theories. When steam propulsion for ships was introduced, the matter became of great practical importance because it was necessary to make estimates for the engine power required to drive a ship at the desired speed. In making such estimates it was necessary to approximate to the value of the water resistance at that speed, although the required engine power was also influenced by the efficiency of the propelling apparatus and propellers. In addition, it was obvious that

the water resistance to the motion of a ship when she was driven by her propellers at a given speed would be in excess of the resistance experienced if she were towed at the same speed, and there was no exact knowledge in regard to that increment of resistance. The earlier mathematical theories of resistance proved to be of little or no service, and they were based on erroneous and incomplete assumptions. Rankine devised a "stream-line" theory which was superior to its predecessors, but it also for a time had no effect on the practice of naval architects. William Froude, adopting this stream-line theory, dealt separately with frictional resistance, and devised a "law of comparison" at corresponding speeds by which from the "residual resistance" of models—exclusive of friction—it became possible to estimate the corresponding residual resistance for ships of similar forms. At first he stood alone in advocating these views, but subsequent experience during forty years has demonstrated their soundness.

Experimental tanks for testing models of ships, such as Froude introduced, are now established in all maritime countries, and the results obtained from them are of enormous value in the designing of steamships. In regard to the selection of the forms of ships, naval architects are now able to proceed with practical certainty; but in the design of screw propellers, even after model experiments have been made with alternative forms of screws, there is still great uncertainty, and dependence upon the results obtained on "progressive" speed trials of ships is

still of the greatest service. As yet the "law of comparison" between model screws and full-sized screws has not been determined accurately. The condition of the water in which screws act, as influenced by the advance of a ship and her frictional wake, the phenomena attending the passage of the water through a screw, and the impression on it of sternward motion from which results the thrust of the propeller, the effect upon that thrust of variations in the forms and areas of the blades of screw propellers, and the causes of "cavitation,"—all form subjects demanding further investigation. In these cases the only hope of finding solutions lies in the association of experimental research with mathematical analysis. There have been very many mathematical theories of the action of screw propellers, but none of these have provided the means for dealing practically with the problems of propeller design, and there is no hope that any purely mathematical investigation ever will do so, because the conditions which should be included in the fundamental equations are complex and to a great extent undetermined.

In connection with other branches of engineering, model experiments have also proved effective. Examples are to be found in connection with the estimates for wind pressure on complicated engineering structures such as girder or cantilever bridges. Experimental methods are also being applied with great advantage to the study of aeronautics and the problems of flight.

The association of the mathematical analysis of past experience with designs for new engineering works of all kinds is both necessary and fruitful of benefits. A striking example of this procedure is to be found in connection with the structural arrangements of ships of unprecedented size, which have to be propelled at high speeds through the roughest seas, to carry heavy loads, to be exposed to great and rapid changes in the distribution of weight and buoyancy, and to be subjected simultaneously to rolling, pitching, and heavy motion, as well as to blows of the sea. In such a case purely mathematical investigation would be useless; the scientific interpretation of past experience and the comparison of results of calculations based on reasonable hypotheses for ships which have seen service with similar results of calculations for ships of new design are the only means which can furnish guidance.

In the past the association of mathematicians and engineers has done much towards securing remarkable advances in engineering practice; and in the future it may be anticipated that still greater results will be attained now that the true place of mathematicians in that practice is better understood.

VIII

MATHEMATICAL CREATION

HENRI POINCARÉ

[THE processes of mathematics, cited by Sir William White, are described with remarkable vividness by Henri Poincaré (1854–1912) in the following extract from *The Foundations of Science* (1913 and 1921). This volume, translated by George Bruce Halstead (1853–   ), is one of a series of books on science and education edited by James McKeen Cattell (1860–   ). The author ranks with such masters as Newton and Einstein. After completing his studies at the École Polytechnique and the École des Mines, and taking his doctorate, he began his career as a teacher of mathematics, mathematical physics, and celestial mechanics in the École Polytechnique. Later he taught at the universities of Caen and Paris, where he achieved the highest distinction. Three of his monographs—nearly five hundred in all—are included in *The Foundations of Science.* The translator, himself a mathematician, has held professorships in several American universities and has translated numerous studies in his chosen field. The editor, Dr. Cattell, an eminent psychologist, formerly of Columbia University, is now President of the Psychological Corporation as well as editor of numerous periodicals devoted to education and science. The passage below is reprinted by permission of The Science Press, of which he is also head.]

What is mathematical creation? It does not consist in making new combinations with mathemat-

ical entities already known. Any one could do that, but the combinations so made would be infinite in number and most of them absolutely without interest. To create consists precisely in not making useless combinations and in making those which are useful. . . . Invention is discernment, choice.

How to make this choice I have before explained; the mathematical facts worthy of being studied are those which, by their analogy with other facts, are capable of leading us to the knowledge of a mathematical law just as experimental facts lead us to the knowledge of a physical law. They are those which reveal to us unsuspected kinship between other facts long known but wrongly believed to be strangers to one another.

To invent, I have said, is to choose; but the word is perhaps not wholly exact. It makes one think of a purchaser before whom are displayed a large number of samples, and who examines them, one after the other, to make a choice. Here the samples would be so numerous that a whole lifetime would not suffice to examine them. This is not the actual state of things. The sterile combinations do not even present themselves to the mind of the inventor.

It is time to penetrate deeper and to see what goes on in the very soul of the mathematician. This, I believe, I can do best by recalling memories of my own. But I shall limit myself to telling how I wrote my first memoir on Fuchsian functions. I beg the reader's pardon . . . I shall say, for example,

that I have found the demonstration of such a theorem under such circumstances. This theorem will have a barbarous name, unfamiliar to many, but that is unimportant; what is of interest for the psychologist is not the theorem but the circumstances.

For fifteen days I strove to prove that there could not be any functions like those I have since called Fuchsian functions. . . . Every day I seated myself at my work table, stayed an hour or two, and tried a great number of combinations, and reached no results. One evening, contrary to custom, I drank black coffee and could not sleep. Ideas rose in crowds; I felt them collide until pairs interlocked, so to speak, making a stable combination. By the next morning I had established the existence of a class of Fuchsian functions, those which come from the hypergeometric series; I had only to write out the results, which took but a few hours.

Then I wanted to represent these functions by the quotient of two series. . . . I asked myself what properties these series must have if they exist, and I succeeded without difficulty in forming the series I have called theta-Fuchsian.

Just at this time I left Caen, where I was then living, to go on a geologic excursion under the auspices of the School of Mines. The changes of travel made me forget my mathematical work. Having reached Coutances, we entered an omnibus. . . . At the moment when I put my foot on the step the idea came to me, without anything in my former thoughts seeming to have paved the way for it, that

the transformations I had used to define the Fuchsian functions are identical with those of non-Euclidean geometry. I did not verify the idea . . . as, upon taking my seat in the omnibus, I went on with a conversation already commenced; but I felt a perfect certainty. On my return to Caen, I verified the result at my leisure.

Then I turned my attention to the study of some arithmetical questions without much success and without a suspicion of any connection with my preceding researches. Disgusted with my failure, I went to spend a few days at the seaside, and thought of something else. One morning, as I was walking on the bluff, the idea came to me, with just the same characteristics of brevity, suddenness, and immediate certainty, that the arithmetic transformations of indeterminate ternary quadratic forms are identical with those of non-Euclidean geometry.

Returned to Caen, I mediated on this result and deduced the consequences. The example of quadratic forms showed me that there are Fuchsian groups other than those corresponding to the hypergeometric series; I saw that I could apply to them the theory of theta-Fuchsian series, and that consequently there exist Fuchsian functions other than those from the hypergeometric series, the ones I then knew. Naturally I set myself to form all these functions. I made a systematic attack upon them and carried all the outworks, one after another. There was one, however, that still held out, whose fall would involve that of the whole place. But all

my efforts only served at first the better to show me the difficulty. . . . All this work was perfectly conscious.

Thereupon I left for Mont-Valérien, where I was to go through my military service. . . . One day, as I was going along the street, the solution of the difficulty which had stopped me suddenly appeared to me. I did not try to go deep into it immediately, and only after my service did I again take up the question. I had all the elements and had only to arrange them and put them together. So I wrote out my final memoir at a single stroke and without difficulty.

Most striking at first is this appearance of sudden illumination, a manifest sign of long, unconscious prior work. The rôle of this unconscious work in mathematical invention appears to me incontestable. . . . Often when one works at a hard question, nothing is accomplished at the first attack. Then one takes a rest, longer or shorter, and sits down anew to the work. During the first half-hour, as before, nothing is found, and then suddenly the decisive idea presents itself to the mind. It might be said that the conscious work has been more fruitful because it has been interrupted and the rest has given back to the mind its force and freshness. But it is more probable that this rest has been filled out with unconscious work, and that the result of this work has afterward revealed itself to the geometer just as in the cases I have cited; only the revelation,

instead of coming during a walk or a journey, has happened during a period of conscious work. . . .

There is another remark to be made about the conditions of this unconscious work . . . it is only fruitful if it is on the one hand preceded and on the other hand followed by a period of conscious work. These sudden inspirations (and the examples already cited sufficiently prove this) never happen except after some days of voluntary effort which has appeared absolutely fruitless. . . . These efforts, then, have not been so sterile as one thinks; they have set a-going the unconscious machine, and without them it would not have moved and would have produced nothing.

The need for the second period of conscious work, after the inspiration, is still easier to understand. It is necessary to put in shape the results of this inspiration, to deduce from them the immediate consequences . . . above all verification is necessary. I have spoken of the feeling of absolute certitude accompanying the inspiration; in the cases cited this feeling was no deceiver. Nor is it usually. But do not think this a rule without exception; often this feeling deceives us without being any the less vivid, and we find it out only when we seek to put on foot the demonstration. I have especially noticed this fact in regard to ideas coming to me in the morning or evening in bed while in a semi-hypnagogic state.

Such are the realities; now for the thoughts they force upon us. The unconscious, or, as we say, the subliminal self, plays an important rôle in mathe-

matical creation. . . . But usually the subliminal self is considered as purely automatic. Now we have seen that mathematical work is not simply mechanical, that it could not be done by a machine, however perfect. It is not merely a question of applying rules, of making the most combinations possible according to certain fixed laws. The combinations so obtained would be exceedingly numerous, useless, and cumbersome. The true work of the inventor consists in choosing among these combinations so as to eliminate the useless ones or rather to avoid the trouble of making them; and the rules which must guide this choice are extremely fine and delicate. It is almost impossible to state them precisely; they are felt rather than formulated. Under these conditions, how imagine a sieve capable of applying them mechanically?

A first hypothesis now presents itself: The subliminal self is in no way inferior to the conscious self; it is not purely automatic; it is capable of discernment; it has tact, delicacy; it knows how to choose, to divine. What do I say? It knows better how to divine than the conscious self, since it succeeds where that has failed. In a word, is not the subliminal self superior to the conscious self? . . .

It is certain that the combinations which present themselves to the mind in a sort of sudden illumination, after an unconscious working somewhat prolonged, are generally useful and fertile combinations, which seem the result of a first impression. Does it follow that the subliminal self, having divined by

a delicate intuition that these combinations would be useful, has formed only these, or has it rather formed many others which were lacking in interest and have remained unconscious?

In this second way of looking at it, all the combinations would be formed in consequence of the automatism of the subliminal self, but only the interesting ones would break into the domain of consciousness. And this is still very mysterious. Why is it that, among the thousand products of our unconscious activity, some are called to pass the threshold, while others remain below? Is it a simple chance which confers this privilege? Evidently not; among all the stimuli of our senses, for example, only the most intense fix our attention, unless it has been drawn to them by other causes. More generally the privileged unconscious phenomena, those susceptible of becoming conscious, are those which, directly or indirectly, affect most profoundly our emotional sensibility.

It may be surprising to see emotional sensibility invoked *à propos* of mathematical demonstrations which, it would seem, can interest only the intellect. This would be to forget the feeling of mathematical beauty, of the harmony of numbers and forms, of geometric elegance. This is a true æsthetic feeling that all real mathematicians know, and surely it belongs to emotional sensibility.

Now, what are the mathematical entities to which we attribute this character of beauty and elegance, and which are capable of developing in us a sort of

æsthetic emotion? They are those whose elements are harmoniously disposed so that the mind without effort can embrace their totality while realizing the details. This harmony is at once a satisfaction of our æsthetic needs and an aid to the mind, sustaining and guiding. And at the same time, in putting under our eyes a well-ordered whole, it makes us foresee a mathematical law. Now, as we have said above, the only mathematical facts worthy of fixing our attention and capable of being useful are those which can teach us a mathematical law. So that we reach the following conclusion: The useful combinations are precisely the most beautiful, those best able to charm this special sensibility that all mathematicians know, but of which the profane are so ignorant as often to be tempted to smile at it.

What happens then? Among the great number of combinations blindly formed by the subliminal self, almost all are without interest and without utility; but just for that reason they are also without effect upon the æsthetic sensibility. Consciousness will never know them; only certain ones are harmonious and, consequently, at once useful and beautiful. They will be capable of touching this special sensibility of the geometer of which I have just spoken, and which, once aroused, will call attention to them, and thus give them occasion to become conscious.

This is only an hypothesis, and yet here is an observation which may confirm it: When a sudden illumination seizes upon the mind of the mathe-

matician, it usually happens that it does not deceive him, but it also sometimes happens, as I have said, that it does not stand the test of verification. Well, we almost always notice that this false idea, had it been true, would have gratified our natural feeling for mathematical elegance.

Thus it is this special æsthetic sensibility which plays the rôle of the delicate sieve of which I spoke.

Yet all the difficulties have not disappeared. The conscious self is narrowly limited; and as for the subliminal self, we know not its limitations. . . . Yet these limitations exist. Is it likely that it is able to form all the possible combinations, whose number would frighten the imagination? Nevertheless, that would seem necessary because, if it produces only a small part of these combinations, and if it makes them at random, there would be small chance that the *good,* the one we should choose, would be found among them.

Perhaps we ought to seek the explanation in that preliminary period of conscious work which always precedes all fruitful unconscious labor. Permit me a rough comparison. Figure the future elements of our combinations as something like the hooked atoms of Epicurus. During the complete repose of the mind, these atoms are motionless; they are, so to speak, hooked to the walls so this complete rest may be indefinitely prolonged without the atoms meeting, and consequently without any combination between them.

On the other hand, during a period of apparent

rest and unconscious work, certain of them are detached from the wall and put in motion. They flash in every direction through the space (I was about to say the room) where they are enclosed, as would, for example, a swarm of gnats or, if you prefer a more learned comparison, the molecules of gas in the kinematic theory of gases. Then their mutual impacts may produce new combinations.

What is the rôle of the preliminary conscious work? It is evidently to mobilize certain of these atoms, to unhook them from the wall and put them in swing. We think we have done no good because we have moved these elements a thousand different ways in seeking to assemble them and have found no satisfactory aggregate. But, after this shaking up imposed upon them by our will, these atoms do not return to their primitive rest. They freely continue their dance.

Now, our will did not choose them at random; it pursued a perfectly determined aim. The mobilized atoms are therefore not any atoms whatsoever; they are those from which we might reasonably expect the desired solution. Then the mobilized atoms undergo impacts which make them enter into combinations among themselves or with other atoms at rest which they struck against in their course. . . .

However it may be, the only combinations that have a chance of forming are those where at least one of the elements is one of those atoms freely chosen by our will. Now, it is evidently among these that is found what I called the "good" combination.

Perhaps this is a way of lessening the paradoxical in the original hypothesis.

Another observation. It never happens that the unconscious work gives us the result of a somewhat long calculation all made, where we have only to apply fixed rules. We might think the wholly automatic subliminal self particularly apt for this sort of work, which is in a way exclusively mechanical. It seems that thinking in the evening upon the factors of a multiplication we might hope to find the product ready made upon our awakening, or again that an algebraic calculation—for example, a verification—would be made unconsciously. Nothing of the sort, as observation proves. All one may hope from these inspirations, fruits of unconscious work, is a point of departure for such calculations. As for the calculations themselves, they must be made in the second period of conscious work, that which follows the inspiration, that in which one verifies the results of this inspiration and deduces their consequences. The rules of these calculations are strict and complicated. They require discipline, attention, will, and, therefore, consciousness. In the subliminal self, on the contrary, reigns what I shall call liberty, if we may give this name to the simple absence of discipline and to the disorder born of chance. Only, this disorder itself permits unexpected combinations.

I shall make a last remark: When above I made certain personal observations, I spoke of a night of excitement when I worked in spite of myself. Such cases are frequent, and it is not necessary that the

abnormal cerebral activity be caused by a physical excitement as in that I mentioned. It seems, in such cases, that one is present at his own unconscious work, made partially perceptible to the over-excited consciousness, yet without having changed its nature. Then we vaguely comprehend what distinguishes the two mechanisms or, if you wish, the working methods of the two egos. And the psychologic observations I have been able to make seem to me to confirm in their general outlines the views I have given.

PHYSICS

IX

THE IMPORTANCE OF PHYSICS TO ENGINEERING

ROBERT ALEXANDER PATTERSON

[As language and mathematics provide the forms of expression necessary for the development and practice of engineering, so physics and chemistry provide the materials essential to its progress. The character of the contributions made by physics is indicated by the following article. The author, Robert Alexander Patterson (1890–), was graduated from Yale College in 1911. Shortly after he obtained his doctorate, he was commissioned in the army of the United States. At the close of the World War, during which he served on the staff of the School of Fire for Field Artillery, at Fort Sill, he retired with the rank of major to resume his duties in the Department of Physics at Yale University. During 1919–1920 he was National Research Fellow at Harvard University. In 1921 he returned to his *alma mater* as Assistant Professor of Physics. Since 1922 he has been Professor of Physics in Rensselaer Polytechnic Institute and, for several summers, Visiting Professor of Physics in Harvard University. He is joint author of papers on optical spectra, x-ray spectra, and crystal analyses.]

Control over the forces of Nature was man's supreme achievement in the nineteenth century. For this achievement a mastery of science and the art of engineering was essential. No event so epito-

mized the century as the growing insight into the processes of the physical world and the application of this knowledge to meet the needs of a progressive civilization. Of the sciences, none proved more fundamental than physics.

Three centuries old as a factor in western civilization, physics has laid the foundation on which the art of engineering has been reared. Delving into the natural phenomena which manifest themselves largely through the eye and ear, and seeking to trace events to their causes, the physicist has revealed a world of law and order subject—within considerable limits—to man's control. With some of the natural sources of energy catalogued, and with the laws formulated under which energy can be released, transformed, distributed, and adapted to human needs, the stage was set for the appearance of the engineer and the development of his profession.

Modern engineering began in the early part of the nineteenth century. Until then, civil engineers, as distinguished from military engineers, were largely engaged in the construction of roads, buildings, bridges, dams, and water wheels, and in surveying. In 1824, the first school of engineering in America was established "for the purpose of instructing persons who may choose to apply themselves in the application of science to the common purposes of life." At this time physics, called "Natural Philosophy," provided the laws of equilibrium according to which structures remain stable and sustain anticipated loads. Nevertheless, it was not until after the

middle of the century that civil engineers abandoned the empirical knowledge of the past as their sole authority and began to design bridges on a sound theoretical basis. The hydrostatic paradox had been understood for three centuries. Yet to-day, many people wonder why a dam built strongly enough to hold back only a small body of water can also withstand the pressure of a lake one hundred miles in length. When locomotives began to speed up, it became necessary for the civil engineer to provide embankments on curves in order that fast trains should not jump the tracks. The design of these embankments is based upon the classical Laws of Motion first clearly formulated by Sir Isaac Newton. That branch of physics that includes the laws that govern equilibrium, the strength of materials as dependent on design, the pressure of fluids, and the forces involved in the motion of material bodies is known as mechanics. In the study of physics, the student of civil engineering finds the fundamental laws that enable him to solve the problems of his chosen profession. Many recent advances in the art are due to the refinement with which these laws are applied in realizing the most economical design consistent with public safety.

In the early years of the nineteenth century, mechanical engineering was just appearing. James Watt had improved the steam engine sufficiently to make it of value to industry. Physicist, for he found it necessary to ascertain by experiment new facts regarding the behavior of steam; inventor, for he

devised contrivances through which this knowledge could be applied, Watt was also a mechanical engineer, for he designed and installed steam engines in industry which performed work on a large scale. In our own country, Robert Fulton applied the steam engine to the propulsion of boats. In 1807 Fulton's *Folly* steamed from New York to Albany. Two decades later, the steam locomotive began to displace draft horses on the railroads. Thus, while the earliest school of engineering was graduating its first civil engineers, industry and transportation were beginning to sense their need of mechanical engineers. Simultaneously, there lived in France a brilliant young physicist, Leonard Sadi Carnot, who formulated the laws by which heat may be transformed into motive power, and specified the conditions under which this may be done most efficiently. Indeed, nearly all advances in heat engine design have consisted of devices—e.g., the mercury turbine—by which the operations recommended by young Carnot can be most nearly approximated in practice.

In addition, the high speed of engines found in locomotives, automobiles, and aeroplanes has necessitated increasing care in the design of moving parts. Each must conform to Newton's Laws of Motion. These laws enable the engineer to foresee the stresses that each must sustain. We have already observed that physics also contributes the laws governing the design of machine members for strength. In it, therefore, the student of mechanical engineer-

ing finds the laws of mechanics and of heat which constitute the basis of his art.

For the prospective chemical engineer the study of physics is no less important. The laws of physics form the basis of theoretical chemistry. To Carnot, who first glimpsed it, and to our own Josiah Willard Gibbs, who formulated, developed, and explored it, we owe that branch of physics known as thermodynamics. It deals with the laws controlling the transformation of energy from one form into another, and particularly with the limitations imposed by Nature upon those transformations that aid men in their work. All chemical processes involve such transformations. Thermodynamics has laid the theoretical foundation of the great boundary science that overlaps both physics and chemistry; and Gibbs has been rightly recognized, first, by Europeans, and then by his own countrymen, as the father of physical chemistry.

To Michael Faraday are due the foundations of electrochemistry,—the laws underlying the arts of electroplating and of electrotyping. To him is due, also, the first conception of the charged ion, which to-day is an essential entity in all chemical theory.

The physicist of the twentieth century is affecting just as profoundly the bases of chemical science. The atom, "indivisible," has been broken into smaller pieces, electrons and protons. Alchemy, the magic art, has been discovered as a natural process in such elements as radium. Indeed, Sir Ernest Rutherford

system by which he could be called to his meals. Enthralled with the search for knowledge, he took no interest in the commercial value of his work,—the typical attitude of great researchers. So it is to the inventors of the nineteenth century—Samuel F. B. Morse, Alexander Graham Bell, Thomas Alva Edison, Elihu Thompson, George Westinghouse, and many others—that we owe the initial application of the discoveries in electricity to the needs of civilization. Although not a few physicists, like Lord Kelvin and our own Henry Rowland, have given generously of their time and thought to effect great advances in the art of applied electricity, scientists in general have always been less interested in practical applications. Their pleasure has been found in the advancement of knowledge for its own sake. The magnification of laboratory experiments on a small scale to accomplishments on a large scale does not seem to attract them. And so a division of labor has taken place. The engineer preëmpts and conveys to society the benefits of the experiments and discoveries of the scientist. This contribution is vital; for he finds practical and economic obstacles that tax his ingenuity to the utmost,—and the joy of solution, coupled with the satisfaction of achievement, is his reward. For success he needs all the knowledge the pure scientist has acquired and all the experience the man of practical arts has accumulated.

Probably the most notable triumph of physics and electrical engineering in the nineteenth century is wireless telegraphy. Its seed sprang from the mind

of Michael Faraday when he conceived of the interaction of electric currents and magnets as taking place by means of forces conveyed continuously through the apparently empty space between them. Neither the existence of the medium in which these forces are transferred nor the existence of the forces themselves within the medium could be established by Faraday. To a large extent they were figments of his imagination,—helpful but imaginary pictures of what might or might not actually be responsible for the actions in which he was interested. Incorporating his ideas in mathematical form, James Clerk Maxwell, a great mathematical physicist, was astonished to find equations which imply that these forces of Faraday are propagated through space with a speed exactly the same as that of light. In this way Maxwell stumbled upon his idea of electromagnetic waves, which, for verification, it was necessary to produce, detect, and measure. This Heinrich Hertz, a young German physicist, accomplished twenty-two years later. Besides measuring the speed and the wave lengths of the invisible waves which he produced, Hertz also showed that in reflection and refraction they obey the same laws as ordinary light. Not only was the existence of Faraday's stresses in the medium thus established, but Maxwell's beautiful electromagnetic theory of the nature of light was experimentally confirmed. With electromagnetic waves actually produced and detected, it did not take many years for Guglielmo Marconi to devise a successful commercial system of wireless telegraphy.

Since then the development of highly evacuated electron tubes and the investigation of their characteristics have resulted in tremendous progress. Out of wireless telegraphy has come wireless telephony, now known as radio. Out of radio is coming television.

In Maxwell's theory and Hertz's experiments the young man interested in radio engineering finds the basis of his art. And no art is being more profoundly influenced by contemporary science.

The science of physics has, therefore, provided the essence out of which modern engineering has evolved during the nineteenth century. Obviously, it had to become the basis of engineering education. Out of the laboratory technique of the physicist of the nineteenth century has come the engineering practice of the engineer of the twentieth. Just as certainly will the laboratory experiments of the present provide the basis of the engineering practice of the future. To-day, the most progressive branch of electrical engineering has to do with communication by high frequency currents and radio waves. Man's ability to broadcast information into millions of homes simultaneously and to talk across the Atlantic Ocean with no intervening wires is due to his knowledge of the motion of electrons inside of highly evacuated discharge tubes. These same tubes are being used to control automatically huge quantities of electrical power. The techniques involved represent the combined achievement of many scientists and engineers during the last two decades. The knowledge revealed by the physicist is being applied daily in the

advance of engineering. Never before has the liaison between the pure scientist in his research laboratory and the engineer been so close and immediate. Television, which will soon be as common as radio, involves discoveries and developments made by physicists in the last five years as well as refinements in the art of telephone communication. Engineers not well versed in the recent discoveries as well as in the classical concepts of physics can contribute little to the development of such arts. To the prospective engineer, therefore, contemporary physics is also important, as well as much more stimulating than the conventional physics of the past. While the latter is the basis of standardized engineering practice, the former will undoubtedly determine the practice that will succeed it. The greatest opportunities lie in undeveloped fields; and the key to these fields is to be found in contemporary science. In the trend of modern physics lies the future of engineering.

Physics offers more than accumulated knowledge to the student of engineering. In the mental habits of the scientist he finds the intellectual force that still directs the progress of engineering. Beginning with careful and accurate descriptions of observed phenomena in words of definite and quantitative meaning, he is disciplined in keenness of observation and precision of statement. Demonstrations of the essential method of science, that of experiment under specific and controllable conditions, are also provided. Not until the sixteenth century was this

method established by Galileo as the most powerful weapon available to the human intellect in its conquest of the forces of Nature. In these demonstrations, those features of the phenomena that are essential and significant are especially emphasized. In the laboratory the student performs experiments, controlling conditions, records observations quantitatively, deduces or computes results, states conclusions, and learns to estimate numerically their accuracy and reliability. No training is more useful to the young engineer than that which inculcates such habits. Realization of the accuracy or inaccuracy of his deductions brings finally confidence in his own judgment because he has learned to recognize and evaluate its limitations.

Observed facts obtained by the experimental method of inquiry constitute the working material and the final criterion of truth for the scientist. When classified and arranged according to mutual relations, laws and theories emerge that illuminate large numbers of these facts. These laws and theories are tools, not realities. By them the scientist hopes to correlate all known facts and predict future events. The practical value of a physical theory lies in the scope of the material it comprehends and in its fertility in suggesting new phenomena to be observed experimentally which will either confirm or modify the theory that has predicated them. With established laws and theories as premises, the student learns to draw conclusions by rigorous, sustained logic as to events that will take place under specified

circumstances. His laboratory experiments confirm or contravert these conclusions. In addition, this kind of reasoning is always involved in the solution of problems. The student is thus drilled in bringing to bear all the mental powers he has developed: analysis; mastery of laws and concepts; accuracy, and concentration. Success is rewarded with a consciousness of achievement, a realization of a certain familiarity with the way in which Nature works, and an appreciation of the power of the mind trained in scientific procedure. What better mental discipline can be suggested for the young engineer, especially since it involves the very concepts, laws, and methods that are the basis of his profession?

A well trained mind is a cultured mind. Realizing the value and limitation of its own thoughts, it is quick to appreciate and respect the thoughts of others. Its interests widen and embrace all phases of human knowledge that affect the civilization in which it is to play a part. Few teachers sensitive to young minds fail to observe this unconscious tendency in all their abler students. Tolerance and good will toward men became natural attitudes. Thus we find even cultural value in the study of physics, the most mechanistic and materialistic of all sciences in the nineteenth century.

Nor is this the only cultural value in the study of physics. As a discipline, physics is fundamental in the education of the cultured man, if by a cultured man we mean one with sympathetic comprehension of the ideals and forces that have molded his civili-

zation and are actively directing it. Science has been and is one of the most powerful influences, if not the most powerful, that is shaping society. Physics deals with man's physical environment. As long as he lives, man will depend upon his physical environment for food and for shelter and even for those agencies by which he communicates with his fellows and moves from place to place. To-day, in view of our tremendous population, civilization rests more than ever upon man's knowledge of and control over his physical environment. Remove but a few of the contributions of physics, and civilization would collapse. Cold, famine, and pestilence would stalk through our large cities. With science as a tool, men carve the destiny of civilization.

Science reveals man as an almost insignificant organism on a tiny sphere in the midst of a vast universe. In his primitive life, he seems to have been buffeted by chance and by terrifying forces. Gifted with the saving power of adjustment, he survived. Having faith in his destiny, he finally hit upon the technique of science as one means of adaptation. Through the power of intellect and patient industry man is learning that he may hew his way to a victorious lordship over the very forces of Nature that once terrified him. An almost insignificant organism, he takes on veritably the appearance of a god.

The story of the struggle of this faith and the faltering development of this technique is an heroic epic. In physics, the student should find some glimpses of this glorious triumph. Great men like

Newton, Faraday, Maxwell, with giant intellects and sensitive temperaments, loom as heroes in history. Beside them, figures like Caesar, Bonaparte, and Bismarck fade into insignificance. The example of men who worked ardently and patiently to know Nature; their great delight in a new discovery, a delight as great as that of an artist before a masterpiece; the inestimable value to humanity of the fruits of their thought and labor; and their unsought but immortal fame,—these are balancing influences in the preparation of young men for their chosen vocations.

Finally, the revelations of the twentieth century have upset the assurance of the physicist of the nineteenth that the laws actuating the physical universe were completely understood. Even the most fundamental of these laws are no longer regarded as generally valid. New processes and agencies—e.g., radioactivity and x-rays—have been discovered where none were dreamed of. Relativity has revolutionized traditional conceptions of time and space. Even the physical world seems to be changing, evolving. Stars burn their very matter into energy of radiation, revealing a new and astounding transformation. The earth seems the residual product of this process out of which man arises and begins his conquest. Cosmical rays of incredibly penetrating power are found at high altitudes, coming from all parts of space, their source believed to lie in the creation of new matter out of stellar radiation. Is creation still going on in our physical uni-

verse? Is our conception of this universe merely a limited glimpse, the reflection of inadequate minds? Mechanistic philosophies fade. Minds that can receive what the study of physics reveals and integrate these revelations with the fruits of other human activities will demonstrate the importance of science to culture and will aid civilization in a quicker realization that the truth shall set men free.

X

MODERN PHYSICS

ROBERT ANDREWS MILLIKAN

[By no scientist has the ideal of truth for its own sake been accepted more absolutely than by the physicist, who, as Professor Patterson has indicated, has contributed more than any other to the progress of engineering; and by no writer has that ideal been formulated more attractively than by Professor Millikan. Robert Andrews Millikan (1868–), educated at Oberlin College, at Columbia University, at the University of Berlin, and at the University of Göttingen, is one of the leading physicists of America. Among the honors which he has received is the Nobel Prize, awarded in 1923. For some time he was Professor of Physics in the University of Chicago, vice-Chairman of the National Research Council, and Chief of the Science and Research Division of the Signal Corps. Since 1921 he has been Director of the Norman Bridge Laboratory of Physics and Chairman of the Executive Council of The California Institute of Technology as well as exchange lecturer at various American and European universities. One of the interesting memorials of these visits is the volume entitled *Evolution in Science and Religion* (1927), which consists of a series of addresses at Yale University. The extract below, forming an introduction to a survey of recent physics, is reprinted, by permission of the author and editor, from the *Proceedings* of the Institute of Electrical Engineers for September, 1917.]

The spirit of modern science is something relatively new in the history of the world, and I want

to give an analysis of what it is. I want to take you up in an aeroplane which flies in time rather than in space, and look down with you upon the high peaks that distinguish the centuries, and let you see what is the distinguishing characteristic of the century in which we live. I think there will be no question at all, if you get far enough out of it so that you can see the woods without having your vision clouded by the proximity of the trees, that the thing which is characteristic of our modern civilization is the spirit of scientific research,—a spirit which first grew up in the subject of physics, and which has spread from that to all other subjects of modern scientific inquiry.

That spirit has three elements. The first is a philosophy; the second is a method, and the third is a faith.

Look first at the philosophy. It is new for the reason that all primitive peoples, and many that are not primitive, have held a philosophy that is both animistic and fatalistic. Every phenomenon which is at all unusual, or for any reason not immediately intelligible, used to be attributed to the direct action of some invisible personal being. Witness the peopling of the woods and streams with spirits, by the Greeks; the miracles and possession by demons, of the Jews; the witchcraft manias of our own Puritan forefathers, only two or three hundred years ago.

That a supine fatalism results from such a phi-

losophy is to be expected; for, according to it, everything that happens is the will of the gods, or the will of some more powerful beings than ourselves. And so, in all the ancient world, and in much of the modern, also, three blind fates sit down in dark and deep inferno and weave out the fates of men. Man himself is not a vital agent in the march of things; he is only a speck, an atom which is hurled hither and thither in the play of mysterious, titanic, uncontrollable forces.

Now, the philosophy of physics, a philosophy which was held at first timidly, always tentatively, always as a mere working hypothesis, but yet held with ever increasing conviction from the time of Galileo, when the experimental method may be said to have had its beginnings, is the exact antithesis of this. Stated in its most sweeping form, it holds that the universe is rationally intelligible, no matter how far from a complete comprehension of it we may now be, or indeed may ever come to be. It believes in the absolute uniformity of Nature. It views the world as a mechanism, every part and every movement of which fits in some definite, invariable way into the other parts and the other movements; and it sets itself the inspiring task of studying every phenomenon in the confident hope that the connections between it and other phenomena can ultimately be found. It will have naught of caprice. Such is the spirit, the attitude, the working hypothesis of all modern science; and this philosophy is in no sense materialistic, because good, and mind, and soul, and

moral values,—these things are all here just as truly as are any physical objects; they must simply be inside and not outside of this matchless mechanism.

Second, as to the method of science. It is a method practically unknown to the ancient world; for that world was essentially subjective in all its thinking, and built up its views of things largely by introspection. The scientific method, on the other hand, is a method which is completely objective. It is the method of the working hypothesis which is ready for the discard the very minute that it fails to work. It is the method which believes in a minute, careful, wholly dispassionate analysis of a situation; and any physicist or engineer who allows the least trace of prejudice or preconception to enter into his study of a given problem violates the most sacred duty of his profession. This present cataclysm, which has set the world back a thousand years in so many ways, has shown us the pitiful spectacle of scientists who have forgotten completely the scientific method, and who have been controlled simply by prejudice and preconception. This fact is no reflection on the scientific method; it merely means that these men have not been able to carry over the methods they use in their science into all the departments of their thinking. The world has been controlled by prejudice and emotionalism so long that reversions still occur; but the fact that these reversions occur does not discredit the scientist,

nor make him disbelieve in his method. Why? Simply because that method has worked; it is working to-day, and its promise of working to-morrow is larger than it has ever been before in the history of the world.

Do you realize that within the life of men now living, within a hundred years, or one hundred and thirty years at most, all the external conditions under which man lives his life in this earth have been more completely revolutionized than during all the ages of recorded history which preceded? My great-grandfather lived essentially the same kind of life, so far as external conditions were concerned, as did his Assyrian prototype six thousand years ago. He went as far as his own legs, or the legs of his horse, could carry him. He dug his ditch, he mowed his hay, with the power of his own two arms, or the power of his wife's two arms, with an occasional lift from his horse or his ox. He carried a dried potato in his pocket to keep off rheumatism, and he worshipped his God in almost the same superstitious way. It was not until the beginning of the nineteenth century that the great discovery of the ages began to be borne in upon the consciousness of mankind through the work of a few patient, indefatigable men who had caught the spirit which Galileo perhaps first notably embodied, and passed on to Newton, to Franklin, to Faraday, to Maxwell, and to the other great architects of the modern scientific world in which we live,—the discovery that man

is not a pawn in a game played by higher powers, that his external as well as his internal destiny is in his own hands.

You may prefer to have me call that not a discovery but a faith. Very well! It is the faith of the scientist, and it is a faith which he will tell you has been justified by works. Take just this one illustration, suggested by the opening remarks of your President. In the mystical, fatalistic ages, electricity was simply the agent of an inscrutable Providence: it was Elijah's fire from Heaven sent down to consume the enemies of Jehovah, or it was Jove's thunderbolt hurled by an angry god; and it was just as impious to study so direct a manifestation of God's power in the world as it would be for a child to study the strap with which he is being punished, or the mental attributes of the father who wields the strap. It was only one hundred and fifty years ago that Franklin sent up his famous kite, and showed that thunder bolts are identical with the sparks which he could draw on a winter's night from his cat's back. Then, thirty years afterward Volta found that he could manufacture them artificially by dipping dissimilar metals into an acid. And, thirty years farther along, Oersted found that, when tamed and running noiselessly along a wire, they will deflect a magnet; and with that discovery the electric battery was born, and the erstwhile blustering thunderbolts were set

the inglorious task of ringing house bells, primarily for the convenience of womankind. Ten years later Faraday found that all he had to do to obtain a current was to move a wire across the pole of a magnet, and in that discovery the dynamo was born, and our modern electrical age, with its electric transmission of power, its electric lighting, its electric telephoning, its electric toasting, its electric foot warming, and its electric milking. All that is an immediate and inevitable consequence of that discovery,—a discovery which grew out of the faith of a few physicists that the most mysterious, the most capricious, and the most terrible of natural phenomena is capable of a rational explanation, and ultimately amenable to human control.

At the end of the nineteenth century there were many physicists and engineers who thought that all the great discoveries had been made. It was a common statement that this was so. I heard it made publicly in 1894; and yet within a year of that time I happened to be present in Berlin at the meeting of the Physical Society at which Röntgen showed his first photographs, and since that time we have had a whole new world, the very existence of which was undreamed of before, opened up to our astonished eyes. We have found a world of electrons which underlies the world of atoms and molecules with which we had been familiar, and the discoveries in that world have poured in so rapidly within

the last twenty years that there are no two decades in human history that compare at all with them in rapidity of advance. And these discoveries have been made for the most part by groups of men interested merely in finding out how Nature works. They have been made almost exclusively by college professors; and for ten years they remained the exclusive property of these professors. What has happened in the last ten years? The industrial world has fallen over itself in its endeavor to get hold of these advances; and by their aid it has increased ten-fold the power of the telephone; it has obtained four or five times as much light as we got a few years ago out of a given amount of electrical power; it has developed new kinds of transformers the existence of which was never dreamed of before. All these things are coming *now*; and how many more are going to come, no man can tell.

And yet we must not focus our attention too intently upon the utility of a discovery. Did you ever hear the story of what happened when Faraday was making before the Royal Society, in 1831, the experiment to which your Chairman referred? He performed his experiment, and then explained it. It was simple; it did not look particularly interesting. And a woman in the audience said, "But, Professor Faraday, of what *use* is it?" His reply was, "Madam, will you tell me of what use is a newborn babe?"—and what a reply it was! Infinite possibilities,—possibilities which may indeed not be realized, but at any rate something *altogether new.*

Faraday did not care about the *immediate* use; for he was one of the great souls who had caught the spirit of Galileo. He knew that human progress depends primarily upon the *growth of the human mind,* the ability of man to get hold of Nature. The utilities might come. They always do come, but they generally crop out as by-products; and the man who has got his mind fixed merely on utilities is simply the man who kills the hen to get the golden egg. I have just as much respect for utilities as anybody has. I believe that nothing is worth while except as it contributes in the end to human progress; but the difficulty is that you cannot tell, nor can I, nor can anybody else, what is going to contribute to human progress. The thing that is important is that the human mind should grow. That is the *sine qua non* of progress.

At the Capitol in Harrisburg is a picture by Sir Edwin Abbey, which is entitled, "Wisdom, or the Spirit of Science." It consists of a veiled figure with the forked lightnings in one hand, and in the other, the owl and the serpent, the symbols of mystery; and beneath is the inscription:

> I am what is, what hath been, and what shall be.
> My veil has been disclosed by none.
> What I have brought forth is this: The sun is born.

It is to lighten man's understanding, to illuminate his path through life, and not merely to make it easy, that science exists. Hence, if you ask me what are the utilities of the particular category of dis-

coveries which I am going to run over here very rapidly, I may be able to tell you of a good many of them; but I shall not try to catalogue them all, because that is not where our immediate interest lies. "Where there is no *vision* the people perish."

CHEMISTRY

XI

THE FOUNDATIONS OF CHEMICAL INDUSTRY

ROBERT ESTAVIEFF ROSE

[Like mathematics and physics, chemistry, also, may be regarded from a utilitarian point of view. Its significance is indicated by Robert Estavieff Rose (1879–) in the following chapter from *Chemistry in Industry* (1924), a compilation edited by Harrison Estell Howe (1881–). The author, educated at the University of Leipzig, taught chemistry at St. Andrew's College, Scotland, and at University College, Nottingham, England, before joining the faculty of the University of Seattle and the staff of the Mellon Institute. Since 1921 he has been Director of the Technical Laboratory of E. I. duPont de Nemours and Company. Like the author, the editor is also a chemist and a man of affairs. After studying at various American universities, he served The Sanilac Sugar Refining Company, The Bausch and Lomb Optical Company, and A. D. Little in various positions. Since the World War he has been an officer of the National Research Council and the Engineering Council. At present he is editor of *Industrial and Engineering Chemistry*. It is therefore fitting that the title-page of *Chemistry in Industry* should bear his name. The chapter by Dr. Rose—the first in the two volumes which have already appeared—is reprinted by permission of the publishers, The Chemical Foundation.]

PRELUDE: THE JUGGLERS

All of us have seen the juggler who entertains by throwing one brightly colored ball after the other

into the air, catching each in turn and throwing it up again until he has a number moving from hand to hand. The system which he keeps in motion has an orderly structure. He changes it by selecting balls of different colors, by altering the course or the sequence of the balls, or by adding to or diminishing the number with which he plays.

With this figure in mind let us use our imaginations. Before us we have an assemblage of hundreds of thousands of jugglers varying in their degree of accomplishment; some handle only one ball, others, more proficient, keep several in motion, and . . . others, of an astounding dexterity, play with a hundred or more at once. The balls they handle are of ninety different colors and sizes. The jugglers do not keep still but move about at varying rates; those handling few and light balls move more quickly than those handling many or heavier ones. These dancers bump into each other, and . . . in certain cases they exchange some of the balls which they are handling, or one juggler takes all of those handled by another; but in no case are the balls allowed to drop.

The Vanishing Point

Now imagine the moving group to become smaller and smaller until the jugglers cease to be visible to us, even when they dance under the highest power microscope. If someone who had not seen them were to come to you and say that he proposed . . .

finding out how the balls were moving and what were the rules of the exchanges made, and, further, that he proposed utilizing his knowledge to control what each minute juggler was doing, you would tell him that his task was hopeless. If the chemist had listened to such advice, there would be no chemical industry; and . . . you would not be living in the way you are.

The jugglers are the electromagnetic forces of matter, the balls are the atoms, and each group in the hands of the juggler is a molecule of a substance. In reality, of course, instead of each molecule being represented by one unit, we should multiply our jugglers by trillions and trillions.

The Master of Molecules

The chemist, without even seeing them, has learned to handle these least units of materials in such a way as to get the arrangements which are more useful from those which are less useful. This power he has acquired as the outcome of his life of research, his desire to understand, even though understanding brought him no material gain. . . . Because of his patience and devotion he has built a number of industries; all have this in common,—they serve to rearrange atoms of molecules or to collect molecules of one kind for the service of man.

The Great Quest

The study of the substances of the earth's crust, of the air over and of the waters under the earth, which has led us to our present knowledge of the electron, atom, and molecule, has been more adventurous than many a great journey made when the world was young, and the frontier of the unknown was not remote from the city walls. Into the unknown world of things upon the "sea that ends not till the world's end" the man of science ventured, and he came back laden with treasure greater than all the gold and precious stones ever taken from the earth. He gave these to others, and he fared forth again. . . . He took no arms upon his quest . . . but, instead, fire, glass, and the most astounding of all tools, the balance. As he pushed farther and farther on his great venture, and as more and more joined his little band, he brought more and more back to those who did not understand in the least what he was doing, until now the lives of all men are made easier, if not happier, by these strange . . . things of which he is the creator by reason of the understanding his journeys have given him,—a power much greater than any mere black magic.

This is the story of some of the strange treasure found by him in the far lands that are about us,—treasure found by learning the secret of the juggler's dance, the dance of the least little things out of which all we know is fashioned.

Sulfuric Acid

THE GREAT DISCOVERY

In Sicily and other parts of the earth where there are volcanoes, lumps of a yellow crumbly "stone" are found, called "brimstone" (a corruption of *brennisteinn,* or burning stone). This material was regarded as having curative properties; if it was burned in a house, the bad odors of the sickroom were suppressed. The alchemists found that it took away the metallic character of most metals, and they considered it important in their search for the philosopher's stone, the talisman that was to turn all things to gold. The alchemists found, also, that sulfur, when burned over water, caused the water to become acid, and one of them found, further, that if the burning took place in the presence of saltpeter, the acid which was produced was much stronger; indeed, if concentrated, it was highly corrosive. A useless find, it seemed, of interest only to the alchemist who hoped to become rich beyond the dreams of avarice and immortal as the gods. But the chemist made this discovery of more importance to the human race than that of Columbus, because by it he gave man a kingdom different from any that could have been his by merely discovering what already existed upon earth. That is the wonder of the chemist's work; he finds that which is not upon the earth until he discovers it. Just as the ártist

creates, so does the chemist. If he did not, there would be no chemical industry to write about.

Experiment to Manufacture

Having investigated this acid, he found it a most valuable tool, with which many new and interesting things could be made. . . . It became necessary, then, if all men were to profit . . . that sulfuric acid should be made easily and cheaply in large quantities. The first attempt at commercial manufacture was in 1740; before that each experimenter made what little he needed for himself. The process, that mentioned above, was carried out in large glass balloons. . . . Then, in 1746, lead chambers were substituted for the glass, and the industry progressed rapidly.

The whole object of this most basic of all chemical industries can be written in three simple little equations:

$$\underset{\text{Sulfur}}{S} + \underset{\text{Oxygen}}{O_2} = \underset{\text{Sulfur Dioxide}}{SO_2}$$

$$\underset{\text{Sulfur Dioxide}}{SO_2} + \underset{\text{Oxygen}}{\tfrac{1}{2}O_2} = \underset{\text{Sulfur Trioxide}}{SO_3}$$

$$\underset{\text{Sulfur Trioxide}}{SO_3} + \underset{\text{Water}}{H_2O} = \underset{\text{Sulfuric Acid}}{H_2SO_4}$$

Of the three elements necessary, oxygen occurs uncombined in the air, of which it forms one-fifth by volume; it is also present combined with other elements in very large quantities in water, sand, and

generally throughout the earth's crust, which is nearly half oxygen in a combined condition.

The Raw Materials

The great storehouse of hydrogen on the earth is water, of which it forms one-ninth, by weight. Sulfur is not so widely distributed in large quantities; but it is very prevalent, being present in all plants and animals and also in such compounds as Epsom salts, gypsum, and Glauber's salt. In the free condition—that is, as sulfur itself—it is found in volcanic regions and also where bacteria have produced it by decomposing the products of plant decay. One other source of sulfur is important, a compound with iron which contains so much sulfur that it will burn.

The problem, then, was to take these substances and from them group the elements in such order as to produce sulfuric acid.

Since sulfur burns readily—that is, unites with oxygen to form sulfur dioxide—one might expect it to take up one more atom of oxygen from the air and become sulfur trioxide. It does, but so slowly that the process would never suffice for commercial production. But there is a way of speeding up the reaction which depends on using another molecule as a go-between, thus making the oxygen more active. The principle is that of the relay. Suppose an outfielder has to throw a ball a very long way. The chances are that the ball will not be true, and that it may fall short of reaching the base. If there

is a fielder between, he can catch the ball and get it to the base with much greater energy.

The chemist uses as a go-between or catalyst (in one process) oxides of nitrogen. Molecules of this gas throw an oxygen atom directly and unfailingly into any sulfur dioxide molecule they meet; then they seize the next oxygen atom that bumps into them and are ready for the next sulfur dioxide molecule. Since molecules in a gas mixture bump into each other roughly five billion times a second, there is a very good chance for the exchange to take place in the great lead chambers . . . into which are poured water molecules (steam), oxygen molecules (air), and sulfur dioxide, to which are added small quantities of the essential oxides of nitrogen.

The Acid Rain

A corrosive, sour drizzle falls to the floor; this is chamber acid. It is sold in a concentration of 70 to 80 per cent. The weak chamber acid is good enough for a great many industrial purposes and is very cheap. If it is to be concentrated, this must be done in vessels of lead . . . and then in platinum or gold-lined stills if stronger acid is needed. Naturally this is expensive, and every effort was made to find a method of making strong sulfuric acid without the necessity of this intermediate step. Especially was this true when the dyestuffs industry began to demand large quantities of tremendously strong sulfuric acid which . . . also contained a considerable

amount of sulfur trioxide dissolved in it (fuming sulfuric acid).

The difficulty was overcome by using another catalyst (platinum) in the place of the oxides of nitrogen. If sulfur dioxide and oxygen (air) are passed over the metal, the two gases unite to form sulfur trioxide much more rapidly. . . . Since platinum is very expensive, and its action depends on the surface exposed, it is spread on asbestos fibers and does not look at all like the shiny metal of the jeweler. This method is known as the "contact process"; and the product is sulfur trioxide, which . . . can be led into ordinary oil of vitriol (98 per cent sulfuric acid) and then diluted with water and brought to 90 per cent acid or left as fuming acid, depending on the requirements of the case . . . when it was tried at first, it was found that the platinum soon lost its virtue as a catalyst; and it was also discovered that the reason was the presence of arsenic in the sulfur dioxide. To get rid of every trace of arsenic is the hardest part of the contact process.

Vitriol

Next time you visit a laboratory ask to be shown a bottle of concentrated sulfuric acid. You will see a colorless, oily liquid, much heavier than water, as you will notice if you lift the bottle. A little on your skin will raise white weals and then dissolve your body; paper is charred by it as by fire. When it touches water, there is a hissing.

Sulfuric Acid and Civilization

A dreadful oil, but its importance to industry is astonishing. If the art of making it were to be lost to-morrow, we should be without steel and all other metals and products of the metallurgical industry. Railroads, airplanes, automobiles, telephones, radios, reinforced concrete,—all would go because the metals are taken from the earth by using dynamite made with sulfuric acid; and for the same reason construction work of all kinds . . . would cease.

We should have to find other ways to produce purified gasoline and lubricating oil. The textile industry would be crippled. We should find ourselves without accumulators, tin cans, galvanized iron, radio outfits, white paper, quick-acting phosphate fertilizers, celluloid, artificial leather, dyestuffs, a great many medicines, and numberless other things into the making of which this acid enters at some stage.

If at some future date, however, all of our sulfur and all of our sulfur ores are burned up, the chemist will find ways of making sulfuric acid. Possibly he may tap the enormous deposits of gypsum which exist in all parts of the earth. . . .

Nitric Acid

It is essential that all the heavy chemicals—that is, the most used acids, alkalies, and salts—should be made so far as possible from readily available

cheap material. We use air, water, and abundant minerals on this account. Nitric acid caused the chemical industry much concern until it was found possible to make it from air, because until then its source was Chile saltpeter, or sodium nitrate, a mineral occurring in quantity only in the arid Chilean highlands. However, this source of supply is still the most important, and the process used is one of great interest.

Having made oil of vitriol, the chemist found that he could produce other acids, one of the most important of these being liberated from saltpeter by the action of sulfuric acid. When nitric acid is made in this fashion, we find that the sulfuric acid is changed into sodium sulfate and remains behind in the still. One might think from this that sulfuric acid is stronger and, on that account, that it drives out nitric acid; but in fact this preparation depends on a very simple principle, one of great importance.

Another Dance

We may best illustrate it by returning to our former simile. Let us assume a sodium nitrate juggler moving rather slowly. He is bumped into by a sulfuric acid juggler moving at about the same rate. They exchange some of the atoms with which they are playing, and in consequence one juggler holds sodium hydrogen sulfate while the other holds nitric acid:

$$NaNO_3 + H_2SO_4 \rightarrow NaHSO_4 + HNO_3$$

The nitric acid molecule does not slow down the juggler so much as the sodium hydrogen sulfate, and therefore this particular dancer moves away rapidly. Suppose millions of these exchanges to be taking place; then the nitric acid molecules will continue to dance away and will not come back to exchange their atoms. If we keep them in by putting a lid on, they are forced to go back, and we get no more than a sort of game of ball in which the hydrogen and sodium atoms are passed back and forth. If, on the other hand, we open the lid and put a fire under the pot, the nitric acid molecules move more rapidly; and sooner or later all of them are driven out.

Nitric acid is now made from the air in more than one way so that we are entirely independent of the beds of Chile saltpeter, no matter what may happen to them. Without nitric acid we could not make gun-cotton, dynamite, TNT, picric acid, ammonium nitrate, and the other explosives which are so important to our civilization. In addition, we would lose all our brilliant dyes and most of our artificial silk. . . .

Salt, The Jewel Box

Soda

Among the treasures to which man fell heir . . . was one of innumerable little cubes made of sodium and chlorine, crystals of salt. These he noticed

whenever seawater evaporated; and he soon found, if he lived on a vegetable diet, as he did in some places, that the addition of these to his food made it more pleasant and savory. In fact, it is a necessity for the health of the human body. Hunting peoples do not use it so much because they live almost entirely on meat, which contains sufficient salt. Next, it was found that salt could be employed for preserving fish and meat, and thus man was able to tide over the periods in which hunting was poor. For ages and ages it was put to no other use. Nobody but a chemist would have thought of doing anything with it. In order to understand the whole of what he did, and the part which salt plays in industry owing to the chemist's activity, we must go back a little.

Soap as a Hair Dye

Very early it was found that the ashes of a fire (and fires at that time were always made of wood) were useful in removing grease from the hands. They were the earliest form of soap; and it is surprising how long they remained the only thing used. Our records show that the Romans were the first of the more civilized peoples to find out how to make real soap; and they learned it from the Gauls, who used the material which they made from wood ashes and goat's tallow for washing their hair and beards. . . . The Romans saw the advantage of soap over wood ashes, and a considerable trade in the making

of various kinds of soaps arose. . . . The advantage of having something more abundant to take the place of the ashes was evident. But the real stimulus which led to the discovery of soda ash came from a different source.

Glass from Ashes and Sand

It was found that ashes heated with sand formed glass. It was also found that the ashes of marine plants, or plants occurring on the seashore, gave a much better glass than that which could be made from the ashes of land plants. In consequence, as the art of glass-making grew, barilla, the ashes of a plant growing in the salt marshes of Spain, became an increasingly important article of commerce; and upon it depended the great glass factories of France and Bohemia. Owing to the political situation which arose at the end of the eighteenth century, France found herself in danger of losing her supremacy in the art of making glass because England cut off her supply of the Spanish ashes. For some reason the French ruler at the time had vision enough to see that it might be possible to make barilla artificially from some source within the kingdom of France, and he offered a prize to any one who would make his country independent of Spain. We have seen that the chemist's business is the transmutation of one kind of material into another, and naturally it was the chemist who came forward with a solution of the problem. Since this process is now supplanted

by a more economical one, we will merely outline it here.

Limestone to Washing Soda

Remember that it is essential to start from some abundant common material. Le Blanc, the chemist who solved the problem, knew that the Spanish ashes contain sodium carbonate, the formula of which we write as Na_2CO_3; that is, it is a combination of sodium, carbon, and oxygen. There are a great many carbonates in Nature; and among these is that of calcium, which we know as chalk, limestone, or marble, depending on the way in which it crystallizes. In this we have a substance of the formula $CaCO_3$. Suppose, then, we write the two compounds side by side: Na_2CO_3, $CaCO_3$. Evidently the only difference is that in one we have two atoms of sodium (Na_2) in place of one of calcium (Ca) in the other. Salt contains sodium and is very common. If, then, we can get the sodium radical from the sodium chloride, and the carbonate radical from the limestone, and join the two pieces, we will get sodium carbonate, which is what we want. What Le Blanc did was to treat sodium chloride with sulfuric acid. This gave him sodium sulfate and hydrochloric acid. Then he heated the sodium sulfate with coke or charcoal and limestone, after which he extracted the mass with water and found that he had sodium carbonate in solution.

The steps do not sound difficult, but it was really

a great feat to make them commercially possible. In the first stage, when sulfuric acid acted on the salt, hydrochloric acid was given off. . . . The amount of it produced exceeded any use that could be found for it, and it was poured away; being highly acid, it undermined the houses in the neighborhood and caused a great deal of trouble. Later, it became the most valuable product of the process because it was converted into bleaching powder by a method that we will take up subsequently.

Industry a Result of Chemical Discovery

It is interesting to learn that this process which France invented in her extremity became one of the largest industrial developments in England. It caused the flourishing there of the sulfuric acid industry because this acid was necessary for the process. . . . It also made possible the development of an enormous textile industry because the making of cloth needs soap and bleach, both of which were first supplied in abundance as a consequence of Le Blanc's discovery.

To return to the story of the chemist's transformations of salt, the present process for the conversion of this compound into sodium carbonate is by the action of ammonia and carbon dioxide upon a saturated solution of it, the carbon dioxide being obtained from limestone. When these three substances are brought together, a change takes place

which can best be described by the following equation:

$$\overset{\text{Ammonia}}{NH_3} + \overset{\text{Water}}{H_2O} + \overset{\text{Carbon Dioxide}}{CO_2} = \overset{\text{Ammonium Bicarbonate}}{NH_4HCO_2}$$

$$\overset{\text{Salt}}{NaCl} + \overset{\text{Amm nium Bicarbonate}}{NH_4HCO_3} = \overset{\text{Sodium Bicarbonate}}{NaHCO_3} + \overset{\text{Ammonium Chloride}}{NH_4Cl}$$

The change that takes place depends on the fact that sodium bicarbonate is comparatively insoluble and separates out. It is collected and then heated, the heat causing it to turn into sodium carbonate, carbon dioxide, and water:

$$2\ NaHCO_3 = Na_2CO_3 + CO_2 + H_2O$$

In this process the essential thing is to keep the ammonia in the system, because it is used over and over again, and, if it escapes, an expense arises out of all proportion to the value of the carbonate, which must be sold at a price of about two cents per pound. The ammonia goes out of the reaction, as indicated in the equation, in the form of ammonium chloride; and this is returned to the process by allowing quicklime, made by heating limestone in kilns, to decompose the chloride. The other part of the limestone (the carbon dioxide) is also used in the process, as shown in the first equation. We start, then, with salt, water, and limestone, and we finish with calcium chloride and sodium carbonate.

CAUSTIC SODA

This is not all that the chemist was able to do with salt. In soap-making much better results are obtained if, instead of using wood ashes, which give us nothing but an impure, soft, potash soap, we use sodium hydroxide or caustic soda. Now, caustic soda is something which does not occur in Nature because it always combines with the carbon dioxide of the air, or with some acid material, and disappears. The old method of making it was to take the soda of the Le Blanc process and treat it with slaked lime. In this way we can make about a 14 per cent solution of caustic soda, which is then evaporated if it is required in a more concentrated form. This method of making caustic soda was sufficiently economical to give us all that we needed at very reasonable prices, but eventually a better method was discovered.

Caustic soda is NaOH; that is to say, it is water (H_2O) in which one of the hydrogens has been replaced by sodium. If in any way we could make this reaction take place, $NaCl + HOH = NaOH + HCl$, we would get directly two products which we want. Unfortunately, it is impossible to get salt to exchange atoms in this way with water. However, a study of salt solutions showed that the atoms of sodium and chlorine were actually separated when in solution, and that they also acquired a property which would allow of their segregation. They be-

came electrically charged, and it is always possible to attract an electrically charged body by using a charged body of opposite sign. If, then, we put the positive and the negative pole of a battery or another source of electricity in a solution of salt, the chlorine will wander away to the positive, and the sodium will wander away to the negative pole.

Electrons

What takes place can best be described by a rough analogy. Suppose two automobiles of different makes are running side by side, keeping together because of the friendship which exists between the two parties. Now suppose these two machines have an accident in which, by a freak, one wheel is torn off one car and added to the other. Assume that the occupants of the car are not damaged and that the cars can still run; also, that the fifth wheel is a distinct nuisance. If there were two garages at considerable distances, one of which specialized in taking off extra wheels, and the other of which did nothing but put on missing wheels, and the accident were a common one involving thousands of machines, then it would be natural for the cars to move in opposite directions to these two garages; and if we assume that all the wheels are interchangeable, there might be a traffic between the garages, by another road perhaps, the wheels being sent from one to the other.

This very rough picture is intended to describe the

fact that when the sodium and chlorine atoms of salt are separated by water, the electrons of which they are composed are distributed in such a way that there is an extra one in the chlorine which (an electron being negative) makes the chlorine particle negative, while the sodium lacks one electron and therefore becomes positive. . . . The result, then, of this electrolysis, or use of the electric current in separating the charged atoms of sodium chloride (the "ions," as they are called), is that sodium and chlorine are given off at the two poles. Now, chlorine is not very soluble in water and can be collected as a gas. The sodium, on the other hand, as each little particle is liberated, reacts with the water about it to give hydrogen and sodium hydroxide. Therefore, we have accomplished what we set out to do, only, instead of getting sodium hydroxide and hydrogen chloride, we get sodium hydroxide, chlorine, and hydrogen.

Electricity

The success of this method is due to discoveries in another field of science. Only when Michael Faraday's researches on the nature of the electric current made available another source of energy different from heat, was it possible for the chemist to carry out what has just been described. . . .

Chlorine

So far we have directed our attention almost entirely to the sodium atom of salt; the other part of the molecule, the chlorine, is also extremely valuable to us. It used to be set free by oxidizing the hydrochloric acid of the Le Blanc process with manganese dioxide. Now, as we have just seen, we get it directly from a solution of salt by electrolysis.

Uses of Caustic Soda

The two servants which the chemist has conjured out of salt by using electricity are extremely valuable, though, if they are not handled rightly, they are equally as dangerous as they are useful when put to work. Caustic soda is a white, waxy-looking solid which is extremely soluble in water and attracts moisture from the air. It is highly corrosive, destroying the skin and attacking a great many substances. When it is allowed to act on cellulose in the form of cotton, the fiber undergoes a change which results in its acquiring greater luster so that the process of "mercerizing," as it is called, is valuable industrially. The manufacture of artificial silk made by the viscose method depends on the fact that caustic soda forms a compound with cellulose. Practically all the soap manufactured at the present time is produced by the action of caustic soda on fat. The by-product of this industry is glycerol, which is used

in making dynamite. In fact, soda is just as important among alkalies as sulfuric acid is among acids.

Uses of Chlorine

Chlorine, the partner of sodium, is a frightfully destructive material. It attacks organic substances of all kinds, destroying them completely, and it also attacks all metals, even platinum and gold, though fortunately, if it is quite dry, it does not react with iron; and on that account it can be stored under pressure in iron cylinders. 'Although it is such a deadly gas if allowed to run wild, it is extremely useful, and its discovery has been very greatly to the advantage of the human race. First of all, it is employed in the manufacture of bleaching powder, a product which enables the cotton industry to work far more intensively than it otherwise could. Formerly cotton was bleached by laying it on the grass, but that is much too slow for our present mode of life. In fact, we have no room for it because it has been calculated that the cotton output of Manchester, England, would require the whole county as a bleaching field. . . . Then came the discovery that this same compound could be used in purifying our water supplies of dangerous disease-breeding bacteria. . . . Now, whenever the water supply of a city is questionable, chlorine is pumped into the mains, or else a solution made from bleaching powder is used. Twenty parts of bleaching powder per million is sufficient to kill

90 to 95 per cent of all the bacteria in the water. For medical use, a solution of hypochlorous acid, which is the active principle of bleaching powder, has been developed into a marvelous treatment for deep-seated wounds; and recoveries which formerly would have been out of the question are now possible. Chlorine is also used in very large amounts in making organic chemicals which the public enjoys as dyestuffs or sometimes does not enjoy as pharmaceuticals or medicines.

All in all, the products obtained from the little salt cube are of . . . importance to everyone of us; and their utilization shows what can be done when men of genius devote themselves to the acquisition of knowledge and then translate their discoveries into commercial enterprises for the benefit of humanity.

XII

THE NATURE AND METHOD OF CHEMISTRY

ALFRED SENIER

[ALTHOUGH chemistry, like mathematics and physics, is a means to an end, it may be regarded as an end in itself, and adventured through delight in the imaginative processes by which it is carried forward. Indeed, it is doubtful whether the highest results can be obtained unless it be approached from the seemingly antagonistic points of view already indicated. Of its method the following extract, constituting the first part of an address delivered before the Chemical Section of the British Association for the Advancement of Science, is notably suggestive. It is reprinted, by permission of the editor, from *Nature*, September 12, 1912. The author, Alfred Senier (1853–1918), educated at the University of Wisconsin, the University of Michigan, and the University of Berlin, was Professor of Chemistry in University College, Galway, Ireland.]

Perhaps there is no intellectual occupation which demands more of the faculty of imagination than the pursuit of chemistry, and perhaps also there is none which responds more generously to the yearnings of the inquirer. It is surely no commonplace occurrence that in experimental laboratories day by day the mysterious recesses of

Nature are disclosed, and facts previously unknown are brought to light. The late Sir Michael Foster, in his presidential address at the Dover meeting, said: "Nature is ever making signs to us, she is ever whispering the beginnings of her secrets." The facts disclosed may have general importance, and necessitate at once changes in theory; and happily, also, they may at once find useful application in the hands of the technologist. Recent examples are the discoveries in radioactivity, which have found a place as an aid to medical and surgical diagnosis and as a method of treatment, and have also led to the necessity of our revising one of the fundamental doctrines of chemistry,—the indivisibility of atoms. But the facts disclosed may not be general or even seem important; they may appear isolated and to have no appreciable bearing on theory and practice—our journals are crowded with such—but he would be a bold man who would venture to predict that the future will not find use for them in both respects. To be the recipient of the confidences of Nature; to realize in all their virgin freshness new facts recognized as positive additions to knowledge is certainly a great and wonderful privilege, one capable of inspiring enthusiasm as few other things can.

While the method of discovery in chemistry may be described, generally, as inductive, all the modes of inference which have come down to us from Aristotle—analogical, inductive, and deductive—are freely used. A hypothesis is framed and tested,

directly or indirectly, by observation and experiment. All the skill, all the resources the inquirer can command, are brought into service; and the hypothesis is established, and becomes part of the theory of science, or is rejected or modified. In framing or modifying hypotheses, imagination is indispensable. It may be that the power of imagination is necessarily limited by what is previously in experience,—that imagination cannot transcend experience; but it does not follow, therefore, that it cannot construct hypotheses capable of leading research. I take it that what imagination actually does is to rearrange experience and put it into new relations; and with each successive discovery it gains in material for this process. In this respect the framing of a hypothesis is like an experiment in which the operator brings matter and energy already existing in Nature into new relations with the object of getting new results. The stronger the imaginative power, the greater the chance of success. The *Times,* in a recent article on science and imagination, says: "It has often been said that the great scientific discoverers . . . see a new truth before they prove it, and the process of proof is only a demonstration of the truth to others and a confirmation of it to their own reason." While never forgetting the tentative nature of a hypothesis, still, until it has been tested and found wanting, one should have confidence or faith in its truthfulness; for nothing but belief in its eventual success can serve to sustain an inquirer's ardor when, as so often hap-

pens, he is met by difficulties well-nigh insuperable. In a well-known passage Faraday says: "The world little knows how many of the thoughts and theories which have passed through the mind of a scientific investigator have been crushed in silence and secrecy by his own severe criticism and adverse examination; that in the most successful instances not a tenth of the suggestions, the hopes, the wishes, the preliminary conclusions have been realized."

But a hypothesis to be useful, to be admitted as a candidate for rank as a scientific theory, must be capable of immediate, or at least of possible, verification. Many years ago, in the old Berlin laboratory in the Georgenstrasse, when our imaginations were wont, as sometimes happened, to soar too far above the working benches, our great leader used to say: "I will listen readily to any suggested hypothesis, but on one condition,—that you show me a method by which it can be tested." As a rule, I confess that we had to return to the work-a-day world, to our bench experiments. No one felt the importance of careful and correct employment of hypotheses more than Liebig. In his Faraday lecture Hofmann says of him: "If he finds his speculation to be contrary to recognized facts, he endeavors to set these facts aside by new experiments, and, failing to do so, he drops the speculation." Again, he gives an illustration of how, on one occasion, not being able to divest himself of a hypothesis, Liebig missed the discovery of the element bromine. While at Kreuznach he made an investigation of the mother

liquor of the well-known salt, and obtained a considerable quantity of a heavy red liquid which he believed to be a chloride of iodine. He found the properties to be different in many respects from chloride of iodine, but he was unable to satisfy all his doubts, and he put the liquid aside. Some months later he received Balard's paper announcing the discovery of bromine, which he recognized at once as the red liquid which he had previously prepared and studied. Thus, though imagination is indispensable to a chemist, and though I think chemists should be, and let us hope are, poets, little can be achieved without a thorough laboratory training; and he who discovers an improved experimental method or a new differentiating reaction is as surely contributing to the advancement of science as he who creates in his imagination the most beautiful and promising hypothesis.

It may never be possible to trace the origin of chemistry, but the historical student has been led, it appears to me, by a sure instinct to search for it in such lands of imaginative story as ancient Egypt and Arabia. Is there anything more fittingly comparable to the marvelous experiences of a chemical laboratory than the wonderful and fascinating stories that have come down to us in *The Arabian Nights,* those monuments of poetic building of which Burton, in the introduction to his great translation, says that in times of official exile in less favored lands, in the wilds of Africa and America, he was lifted in imagination by the jinn out of his dull surroundings, and was borne off by them to his beloved Arabia,

where, under diaphanous skies, he would see again "the evening star hanging like a golden lamp from the pure front of the western firmament; the after-glow transfiguring and transforming as by magic the gazelle-brown and tawny-clay tints and the homely and rugged features of the scene into a fairyland lit with a light which never shines on other soils or seas?" I cannot help thinking that the study of such books as this, the habit of exercising the imagination by reconstructing the scenes of beauty and enchantment which they describe, might do much to strengthen and sharpen the imaginative faculty, and might greatly increase its efficiency as an indispensable tool in the hands of the pioneer who seeks to extend the boundaries of knowledge. The *Times*, in the article already quoted, says that, as with a Shakespeare, "it is the same with imaginative discoverers in science. . . . But the faculty is not merely a fairy gift that can be exercised without pains. As the sense of right is trained by right action, so the sense of truth is trained by right thinking and by all the labor which it involves. That is as true of the artist as of the man of science; and one of the greatest achievements of science has been to prove this fact, and so to justify the imagination and distinguish it from fancy."

Again, let it not be forgotten that chemistry in its highest sense—that is, in its most general and useful sense—is purely a world of the imagination, is purely conceptual. And in addition to this, more-over, it is based, like all science, on the underlying

assumption of the uniformity of Nature, an assumption incapable of proof. If we think of the science as a body of abstract general theory, and exclude for the moment from our view its innumerable practical applications, and also all special individual facts not yet known to be related to general theory, then what remains are the more or less general facts or laws. These it is which give the power of prediction in new cases of similar character, the power of foresight by which the claim of chemistry to its position as a science is justified. Chemistry, as such, is an ideal structure of the imagination, a gigantic fairy palace, and, be it noted, can continue to exist only so long as there are minds capable of reproducing it. Think of all the speculation—and speculation, too, of the highest utility when translated into concrete applications—about the internal structure of molecules. I venture to say that the most magnificent creations of the greatest architects are not more elaborate, nor more beautiful, nor more fairy-like, than the chemist's conception of intramolecular structure and the magical transformations of which molecules are capable; and yet no one has had direct sensuous experience of any molecule or atom, nor possibly ever will have. But although the conceptual nature of the science is unquestionable, it certainly contains truth in some form as tested by concrete realization and correctness of prediction; and during the last century or two it has undoubtedly given to man a mastery over Nature of which he had never dreamed.

IMAGINATION AND INVENTION

III

MECHANISM AND CULTURE

JAMES THOMSON SHOTWELL

[The preceding chapters reflect the point of view of the scientist and the engineer. The next two chapters, sharply differentiated in temper, indicate the attitude of the historian and the philosopher toward the civilization created by their achievements. James Thomson Shotwell (1874–), the author of the first of these essays, was educated at the University of Toronto and at Columbia University. Since 1900 he has been connected with the latter institution. During the World War he was Chairman of the National Board for Historical Service; and after the Armistice, a member of Preparatory Commission for the Peace Conference, at which he served as Chief of the Division of History. At the Peace Conference he was also a member of the Commission on International Labor Legislation. Since 1924 he has been Director of the Division of Economics and History of the Carnegie Endowment for International Peace. He is the author and editor of many volumes dealing with the origins and results of the World War, with labor problems, and with international relations. His article, a brilliant exposition, from the point of view of imagination and art, of the place of invention and mechanism in society, is reprinted, by permission of the author and editor, from the *Historical Outlook,* January, 1925.]

Socrates, according to Plato, lamented the passing of that time in Greece when the only known facts

about the past were those treasured in the memory of the tribal bard and the coming of that degenerate age when people no longer would bother remembering things they could read in books. He deprecated the invention of writing. Yet it was by the written page of his pupil Plato that the conversations in the cool gardens on the outskirts of Athens have survived, to secure his own immortality.

This objection of Socrates to the invention of an alphabet was something more than the proposition of a philosopher in need of an argument. It was a protest against mechanism. Making black marks on Egyptian papyri or skins from Asia—those skins the merchants of Pergamum later made into parchments (*pergamenta*)—compares with reciting an epic as the use of machinery compares with hand labor. Socrates, we suppose, would have preferred telling the time by a guess at the lengthening shadow on the square rather than by the use of such an instrument as a watch. By ignoring inventions one kept "close to Nature."

This is an attitude to be found throughout the whole history of culture. Its most earnest advocates have been the artists, impatient of anything interposed between Nature and the individual. But idealists generally have joined in the denunciation or shared the contempt for mechanism, no matter what their field. Literature has held aloof, except in patronizing, romantic moods, until the present. History has ignored the very implements of progress—the tools of work, the mechanism of effort—even

while recording the results. There has, therefore, developed a gulf between "culture" and achievement which has widened with each new invention.

There have been, in recent years, some signs of a revolt against the conspiracy of the poetically-minded to ignore the creations of the practically-minded, but unless the revolt becomes a revolution we shall never square ourselves with reality. If we are to make anything intelligent out of the world we live in, we must free ourselves from this romantic sentimentality, which goes back to Socrates and beyond. Idealism, left to itself, is futility. There is no sadder fact in the tragic circumstances of the present than that idealism failed to avert the desolation of Europe. It will always fail, so long as it holds itself aloof from the grimy facts of daily life.

Like the forces of Nature, ideas must be harnessed and set to work, or things will remain exactly as they were before. One cannot weave cloth with an idea, but embody the idea in wood and iron and it will replace all the hand-loom workers in the world. Wherever a locomotive sends its puff of steam through the smokestack, the idea of George Stephenson is at work,—an idea that a forced draught on the fire would give the engine enough power to pull its load. There are spindle whorls in the Grimaldi caves along the slopes of Menton, used by the fingers of spinning women of the late Stone Age, over 10,000 years ago. How often in all that stretch of years have spinners dreamed of something to carry on the motion of the whorl be-

about the past were those treasured in the memory of the tribal bard and the coming of that degenerate age when people no longer would bother remembering things they could read in books. He deprecated the invention of writing. Yet it was by the written page of his pupil Plato that the conversations in the cool gardens on the outskirts of Athens have survived, to secure his own immortality.

This objection of Socrates to the invention of an alphabet was something more than the proposition of a philosopher in need of an argument. It was a protest against mechanism. Making black marks on Egyptian papyri or skins from Asia—those skins the merchants of Pergamum later made into parchments (*pergamenta*)—compares with reciting an epic as the use of machinery compares with hand labor. Socrates, we suppose, would have preferred telling the time by a guess at the lengthening shadow on the square rather than by the use of such an instrument as a watch. By ignoring inventions one kept "close to Nature."

This is an attitude to be found throughout the whole history of culture. Its most earnest advocates have been the artists, impatient of anything interposed between Nature and the individual. But idealists generally have joined in the denunciation or shared the contempt for mechanism, no matter what their field. Literature has held aloof, except in patronizing, romantic moods, until the present. History has ignored the very implements of progress—the tools of work, the mechanism of effort—even

while recording the results. There has, therefore, developed a gulf between "culture" and achievement which has widened with each new invention.

There have been, in recent years, some signs of a revolt against the conspiracy of the poetically-minded to ignore the creations of the practically-minded, but unless the revolt becomes a revolution we shall never square ourselves with reality. If we are to make anything intelligent out of the world we live in, we must free ourselves from this romantic sentimentality, which goes back to Socrates and beyond. Idealism, left to itself, is futility. There is no sadder fact in the tragic circumstances of the present than that idealism failed to avert the desolation of Europe. It will always fail, so long as it holds itself aloof from the grimy facts of daily life.

Like the forces of Nature, ideas must be harnessed and set to work, or things will remain exactly as they were before. One cannot weave cloth with an idea, but embody the idea in wood and iron and it will replace all the hand-loom workers in the world. Wherever a locomotive sends its puff of steam through the smokestack, the idea of George Stephenson is at work,—an idea that a forced draught on the fire would give the engine enough power to pull its load. There are spindle whorls in the Grimaldi caves along the slopes of Menton, used by the fingers of spinning women of the late Stone Age, over 10,000 years ago. How often in all that stretch of years have spinners dreamed of something to carry on the motion of the whorl be-

sides the arm and hand! Out of such longings came —no one knows from where—the simple spinning wheels of the Middle Ages. Yet it was only in the eighteenth century that a tinkering watchmaker helped Arkwright to get his roller-frame to work, and spinning passed forever from the fireside to the mill. New cities arose by the marshy waste of Lancashire; and the shipping of Britain, carrying its goods overseas, made possible a new world empire, —not created in a fit of absentmindedness, as an idealist historian declared, but through the might of the Industrial Revolution.

Few students of literature stop to think that its existence depends upon paper and ink as well as thought! The records of history depend upon the cutting of the chisel in the stone, the sharp impress of the scratching stick, on clay or on wax tablet, the scrawl of charcoal or ink on leaves of trees, papyri wrappings, or leather. Before these devices were used lie the unnumbered centuries of that period we call the prehistoric; this side of it, is the world of history. History begins with writing; the prehistoric, as we use the term, is a synonym for the preliterate. History depends upon that mechanism which transfers thought from brains to material substances, and so enables thought to endure while the thinkers come and go.

It is strange that the extent to which thought depends upon mechanism for its preservation seldom occurs to us except when the mechanism fails. We know that the burning of the library at Alexandria

blotted out for all time much of the culture of the distant antiquity which it had gathered in the papyri on its shelves. We know as well that the last classics of Greece and Rome perished in the moldy rolls of papyri which could not last in the climate of the northern Mediterranean as they do in Egypt. The book trade of the ancients was careless of the future —as ours is to-day. But had it not been for papyri rolls dealt in by those astute traders who brought their goods to the wharves of Athens and Ostia, it is doubtful if the literature of classic Greece and Rome would have been produced at all. Had there been nothing better than clay tablets to scratch, how would the Augustan Age have achieved what it did? Imagine Dante in his exile, accumulating the mud cylinders necessary for the *Divine Comedy*. Or, to bring the matter down to our own time, what would our modern literature and journalism amount to if the Arabs had not invented paper? A printing press without paper is unthinkable; and literature cannot exist without them both. We need a Sartor Resartus in the history of literature to show us how naked and helplessly limited is thought except when provided with mechanism.

There have been two great creative epochs in the history of our civilization; that of ancient Greece and that of to-day. The one produced critical thought; the other applied it to produce machines. Besides these two contributions to secular society, all others rank as minor. The one stirred into activity that critical intelligence upon which rests our whole

apparatus of knowledge; the other made Nature our ally not merely by applying its power to do our work, but also by supplying the means for extending knowledge itself, almost to the infinite. Seen in this light, the protest of our modern humanists against mechanism has little of that insight into reality which was the characteristic note of Socrates.

What is needed in both humanists and scientists is the Hellenic sense of just proportion, so that neither thought nor machines shall become master of life. For thought turned upon itself, divorced from the setting in a real world, becomes as idle as the speculations of the schoolmen; and machines become, not instruments for human liberation, but the dominant element in society. Education in a modern world must respond to both these demands. It cannot be purely literary or idealistic without losing touch with the spirit of the age in which we live; it cannot be purely technical and remain education.

How many of us realize that a steam engine is as genuinely an historic product, as fittingly the symbol of an age, as the feudal castle or the mediæval cathedral? that a modern factory is as much the center of historical forces as the ancient city?

We shall never see the true perspective of history so long as we accept unquestioned the mediocre outlook of what we call common-sense people. We need imagination and insight even more than judgment; for otherwise our judgments simply circumscribe and limit our activities. If there were only one factory in the world, if the power that Watt

released from the coal mines were so concentrated that instead of invading every hamlet of the civilized world it was confined to the single valley of the Clyde and drew to it there the work of the world, we should have some feeling for the importance in history of one of the great inventions. But instead, its effects penetrate the environment of common life everywhere, and so we miss its meaning.

Invention is an art. It is the projection into matter itself of the conscious will. It makes matter a part of the agency of control and also a part of intelligence. Loose grains of muddy ore, lying in the bosom of the hills, become iron axes. They have nothing in themselves to indicate axes. They might, if placed too close to a fire, under certain circumstances become hardened into a mass. But while the ore is merely matter, the ax is matter plus mind. It bears the impress of intelligence, and that to so great a degree that the anthropologists passing before the rows of axes in the cases at a museum can reconstruct from their form and composition the state of culture of the makers, like a pianist whose symphonies arise from the keys of his piano. The ax implies both consciousness and purpose; it means cutting. The same is even true of a forked stick which the savage uses as a spade, though here the injection of the human element into the material is less obvious, because the object has not been refashioned. The fork was a result of its nature as a branch; that is, a part of a vegetable mechanism for catching air in leaves and conveying nitrogen to the

trunk. It was not produced by Nature to dig potatoes. Nature leaves the branch in the air and the potato in the ground. But in the hands of man the fibers of wood, like the particles of iron, are turned into something else; they become part of conscious action, a continuation of muscle and an agency of mind. The potentialities of the tool are those of the brain that conceived it and controlled the fashioning hand, as much as they are those of matter. Invention is a projection of consciousness into the unconscious; a creation.

If this can be said at the dawn of invention, and of a tool like a digging stick, which itself embodies no thought, which is not a tool except when so regarded or used, the utility of which is accidental, it is abundantly evident when invention produces not a tool but a machine. The difference between a tool and a machine is that the tool helps a man to do his work, but the machine does the work itself. The man changes his position entirely with reference to it. His business with the machine is simply to make it work. The factory operative does no spinning; he mends threads and makes the spindles spin, forces the steam to move the iron and the iron to transmit its energy to the whirling spools, and they in turn to gather up that energy and imprison it in the spirals of thread or yarn, where our fingers later may find it stored up,—a source of strength against strains and pulls. The factory spinner merely assists at this transformation like the impresario at a theater. Steam and iron and fiber dance before him

into new combinations like a dream from the Arabian Nights.

The machines that do these things are the perpetuation of the initial energy of their inventors. In the steam engine, for instance, Papin, Newcomen, and Watt have found an immortality larger than we have yet realized. In its gliding rods and noiseless wheels the brain of the inventor lives as that of Virgil in the *Æneid*. But while the art of the one is cast cathedral-like, in static mold, to resist the forces of time by its perfection and its strength, that of the other—the invention—is thrown, as it were, into the crucible of change and creates itself the forces that reveal its imperfections and weakness. The engine develops the speed that breaks it down. Yet the immortality of the invention is perhaps the surer of the two; for it enlists its destroyer as its ally. It becomes part of change itself, and so gains some control over it. It sets going the irrecoverable march of events, which make up what we call time, and becomes an integral part of the ever-fleeting present. For its immortality lies in its use. By the work it does it disturbs the poise of phenomena so that once started it creates the demand for its own continuance. It contains its own stimulation; for its imperfections call as much for further invention as its successes encourage to new ones. So it is a social phenomenon of the most complex nature. If it immortalizes the Watts and Arkwrights, it is only by merging their creations in those of a vast composite whole. The original engine of Watts

and spinning frame of Arkwright are in museums; but both machines are also preserved wherever engines are at work or cotton is being spun. The original inventors have become contributors to a more august creation than they guessed. The brain of the individual scientist or mechanic fuses its creation (steam valve or automatic brake) into those of all society and all future time. It will live only so long as it can be adjusted to the changing machine. Each bolt and bar, each wheel or crank, is the crystallized thought of some nameless engineer. When they fit and go, the structure lives, and each part is instinct with life. Apart or unfitted, they die. The cylinder that might hold the power to drive ocean liners is good only for the scrap-heap unless the pistons fit and the gearings work. And so, if one could imagine the whole dynamic force of the Industrial Revolution gathered together and concentrated in a single cylinder, with a power to which that of Niagara would be like that of a rivulet, it would be as useless as the energy of ocean tides to-day, unless there were the nicest adjustment in the parts of the machine. Machinery is a social creation and is itself a sort of society!

Thus, in the social preservation of inventive thought, by a strange paradox, this individualistic age is the annihilation of the individual. Its greatest art creation, machinery, it maintains and treasures only so long as the individual contributions are in tune with the whole.

There are two kinds of immortality: the immor-

tality of monuments, of things to look at and recall; and the immortality of use, of things which surrender their identity but continue to live, things forgotten but treasured, and incorporated in the vital forces of society. Thought can achieve both kinds. It embodies itself in forms—like epics, cathedrals, and even engines—where the endurance depends upon the nature of the stuff used, the perfection of the workmanship, and the fortunes of time. But it also embodies itself in use; that is, it can continue to work, enter into other thought, and continue to emit its energy even when its original mold is broken up.

It is the first kind of immortality—the monumental kind—which has mainly drawn our attention; for it is clearer, if not larger, in our consciousness. Use, on the other hand, obliterates outlines so that the things used most are often least seen. So in keeping with our natural tendency to visualize our thought even in the things of use, as if to make up for this indistinctness, we encourage the perpetuation of form—in institutions and traditions—and enshrine it in art.

Let us be clear about this monumental side. Poems live in themselves and not simply as stimulations to deeds or other thoughts. Form imposes itself on thought and preserves by means of its external beauty, even though it is often only a successful distortion of the thought with which it started. Cathedrals stand before us out of the Middle Ages which created them, defying time in their own right, by the double strength of poise and beauty in stately

columns and towering walls. These formal perpetuations of thought in its own expression are the most appreciated, as they are the most obvious. They require no penetrating analysis to detect; they are matters of pure observation. Thought grips materials without effort, but hesitates to tackle thought; so the concrete world lodges in the memory while the abstractions slip by unnoticed.

So important is this formal apprehension of things that it has been taken at its face value by society, as society takes things at their face value (which includes, of course, the value of the face, not simply its looks), and made synonymous with art; as if there were not a greater art in the mastery of those intangible, elusive forces which have escaped from their mold and penetrate wherever thought can go, the art of mathematics, science, and invention. Indeed, the same tendency which makes us see the obvious first and prize it most carries us still further. It tends to become a sort of sacramental attitude, consecrating not only the form in which the thought is cast, but the material embodied in it and the environment which molded it. The tongue of Dante, of Luther, and of the King James Bible are monuments of such consecration. We even carry this sacramentalism to its primitive conclusion. Although we know better, a strain of fetish worship runs through all of us. The bones of men receive our reverence, as if in them resided—or resides—the efficacy of their thought and action. Placards are posted where thinkers have lived and died, as if

their thought belonged like some haunting spirit to walls and garden walks.

Now all of this is legitimate enough so long as much of our thought is sacramental and our feelings stir with fetishistic suggestions at historic sites or relics. But it obscures the larger life and the truer immortality of thought, the immortality of use. Dante's vision has entered into many a scheme of the world besides that into which he wove the picture of the Florence of his day. In fact, for centuries it molded the cosmology of all Christendom, and it still colors the common dream of immortality. It is this larger vision, built of the universal hope and fear, that is the real *Divina Commedia,* not the epic locked in its stubborn Tuscan rhymes. No form of art, however perfect, can imprison or contain all of a living thought. If thought is alive it is more than its form. It will escape and live. Often it carries with it in its new use broken fragments of its form, and so may still be recognized at sight, as the architecture which produced the mediæval cathedral breaks up into the buttressed piles of a modern city, a dome here, a flying arch there, walls soaring for the light, towers that carry forever the memories of Italy, but all disparate and merged into a new creation. This new creation, however, is no massive, self-contained whole; it is instinct with life and change. It is not static like the old, but eternally recreating itself, replacing arches and domes by girdles, and leaving the old architecture behind with the problems it faced and the material it faced them

with. The one imperishable thing is the science of which these are the fleeting traces.

It is the same with history as with art. At first glance what one sees in it is the formal event, the embodied institution, the externals of things. But when we look deeper we find what happens in a given time and place is only a part of the real event. The cause and results are also parts of it. The result is merely the prolongation of the event in other circumstances, the releasing or the destruction of its potentialities. Battles are more than charging cavalry and riddled squares; they are not over when the firing ceases. They still continue in the hatreds and enthusiasms they arouse, in policies of state, in armaments, in nations themselves. The German Empire was Sedan crystallized,—Sedan and other things. The battle itself is only the most concentrated form of an event, just as a poem is the most perfect expression of an idea. But the real significance, the essence of both is something larger than the form, however concentrated or complete it seems.

Now, it is in the same way that the cylinder springs and separate condensers of Watt's first engine are curiosities for the historian; but the idea, the creative power, of that invention is moving on with all the forces of the Industrial Revolution. It was born of an application of Scottish ingenuity to Scottish thrift; for all that Watt had in mind when he set to work was to save coal by making an engine that did not have to heat a cool cylinder at every

stroke. But the engine that was invented to save coal, in its generation of power, has eaten into the heart of every coal deposit of Britain, while the power it releases has not merely changed the material environment of civilization, but actually brought millions of human beings into existence—each with his and her own world of thought and work—in the stimulation of population through the production of wealth.

Indeed in a sense one may say that machines—the product and embodiment of invention—attain a sort of life of their own. They enter the field of industry to play their own rôle, always incalculable, often achieving what their creators never dreamed of and the opposite of what they intended. They are not simply aids to labor, doing more things than the hand worker, producing more and more things of the same kind, in an endless addition to the stock of goods. They are changing the mental and moral outlook of society as well as its physical basis. To what extent they do this must be left to a consideration of the economic interpretation of history. But when even philosophy (in the metaphysics of Bergson), recognizes that the machine steps, as it were, into the main problem of life, adjustment, and adaptation—and so becomes an element, and the largest element—in this present phase of our biological evolution, it is time for history to wake up to this tremendous fact. It is not a fact for economists or philosophers alone. Not only is it, in itself, an event of keen human interest, clear defini-

tion, and notable prominence, but it underlies every other event of large importance in the political history of the last half-century. The Industrial Revolution and the machine will inevitably furnish the central axis of those histories of the future which deal with our era, as Bergson says. It is our privilege even now to see how magnificent the text will be.

XIV

WHERE IS INDUSTRIALISM GOING?

BERTRAND RUSSELL

[As might be expected, there are many critics who do not share Professor Shotwell's belief that invention is the servant of imagination. One of them is Mr. Bertrand Russell (1872–), now engaged in a novel educational experiment at the Beacon Hill School, Harting, Petersfield, England. A son of Viscount Amberley and heir presumptive to the Earl of Russell, as well as a graduate and former fellow of Trinity College, Cambridge, he has inherited the rich culture of an ancient house and a sophisticated civilization. His approach to contemporary problems, however, has never been conventional. Distinguished as a mathematician, a scientist, and a philosopher, he has gradually extended his interests in the social sciences,—a field in which, as an original and daring thinker, he has often run counter to current ideals. His essay, which first appeared in the *Century Magazine,* November, 1923, and which is reprinted, by special arrangement, from *The Prospects of Industrial Civilization* (1923), published by the Century Company, is a challenge to those who are inclined to accept too complacently the results of modern industrialism.]

The indispensable conditions for the existence of industrialism in a community may be said to be: large organizations of workers engaged upon a common task; willingness in the directors of industry to fore-

go present goods for future profit; an orderly and stable government, skilled workers, and scientific knowledge. Assuming that the conditions for the growth of industrialism exist, I want, in this paper to inquire what effects its growth is likely to have if it is not counterbalanced by other tendencies.

Industrialism does not consist merely in larger undertakings requiring a great number of workmen. The building of the pyramids was a vast undertaking, but was not industrial. The essence of industrialism is the employment of elaborate machinery and other means, such as railways, of diminishing the total labor of production. All the characteristics of industrialism are exemplified by the substitution of a bridge for a ferry, in spite of the fact that bridges existed before the industrial era. If a small number of men wish to cross a river, less labor is involved in taking them across in a boat than in building a bridge. But when very many wish to cross, the bridge involves an economy of labor, in spite of the fact that it is a much more serious matter to make a bridge than to make a boat. It is obvious, also, that the building of a bridge, except for military purposes, depends upon the expected preservation of some degree of law and order, both because a bridge is easily destroyed and because, in very unsettled times, no one can spare energy or thought for objects of which the advantage is in a more or less distant future.

The essence of industrialism is the expenditure of much joint labor upon things that are not themselves

consumable commodities, but merely means to the production of other things that are consumable. From this fundamental quality all the other characteristics of industrialism follow.

The first thing to notice is that industrialism makes a society more organic, in the same sense in which the human body, which is a collection of cells, is more organic than a crowd of protozoa each consisting of a single cell. Each of the protozoa is capable of all the functions required for keeping alive; it does not need help from the others, and it does not die because they die. The cells composing the human body have no such independence; they have different functions, all necessary or at least useful for the life of the whole, and when any of the organs that perform vital functions are destroyed, the rest perish. The eyes can only see, the ears can only hear, and so on; an eye or an ear severed from the rest of the body cannot do what is necessary to keep alive, as the protozoa can. *In this sacrifice of independence to coöperation* there is both loss and gain. There is loss in the fact that the whole assemblage of cells can be killed by one vital wound, and that, therefore, a human body has a more precarious life than a crowd of protozoa. But there is gain in the fact that by specializing the several organs become capable of doing work that no number of protozoa could do, and that the life of a human body is thus enriched and its responsiveness to its environment enormously enhanced. Exactly parallel differences exist between an industrial and an unindustrial society.

In a primitive pastoral or agricultural community, each family produces all that is needed for its own subsistence. The happiness of such a family has been depicted by Pope in the poem beginning:

> Happy the man whose wish and care
> A few paternal acres bound.

But it may be doubted whether Pope would really have liked this state of affairs, since it would not have enabled a man to live by the sale of his verses. A society that allows such specialization is really on the road to industrialism.

In an industrial community no man is self-subsistent; each man takes a part in a process that produces a great deal of some commodity or of some machine for making commodities, but no man produces the whole variety of commodities necessary for preserving life. Hence, trading, or at any rate, some form of exchange of products is absolutely necessary to survival wherever industry exists. The man engaged in a factory has to be fed and clothed by the labor of others and cannot even produce what is made in the factory without the machinery and the coöperation of the other workers. He has ceased altogether to be an economically independent unit. The capitalist is at least equally dependent; if men would not work for him, he would starve. Agriculture, as it becomes more scientific, shares, though to a lesser degree, in the tendencies of industry, as in the large-scale farming of the United States; it requires manures and machines that cannot be pro-

duced on the spot, but are often brought from great distances. Thus the whole community becomes knit together, so that the life of each depends upon the life of all.

Like the human body, an industrial society has its vital organs, the destruction of which paralyzes the whole organism. This becomes increasingly true as industry becomes more advanced and scientific. The destruction of a power station may cause all the factories, trams, lights, and electric trains of a district to cease working. This is merely an example of the universal law that what is more highly organized is more sensitive. It follows that lawlessness and destructiveness can do far more harm in an industrial community than they can where the methods of production are more primitive.

As society grows more organic, it is inevitable that government acquires more importance. The acts of individuals have more and more far-reaching effects upon others, and therefore require to be more and more controlled in the interests of the community. Hence a diminution of individual liberty and of what may be called the anarchic side of life, that is, the side in which a man merely follows his own whims. If this side of life is to be in any degree preserved under industrialism, special measures will have to be taken to that end.

Against the loss of liberty due to increase of government and organization, there is to be set a gain of liberty owing to the fact that the necessaries of life can be produced with less labor than in a pre-

industrial society. The desires of an individual are subject to two kinds of restraint; namely, those due to the community and those due to material conditions. Industrialism, while it tends to increase the former, greatly diminishes the latter. The restraints imposed by material conditions are primarily those involved in warding off death. Most animals, owing to lack of foresight, die by starvation. Most human beings, owing to their possession of some slight degree of foresight, succeed in avoiding this form of death. But in a pre-industrial society they only succeed, unless they belong to the rich minority, by working hard almost all their lives in the production of food and other necessaries. This work is in itself often irksome from its excessive amount, and is a complete obstacle to the realization of all desires for knowledge, beauty, or enjoyment. Such desires, where industry is undeveloped, can only be indulged by the fortunate few, kings, priests, and nobles. But under industrialism the production of necessaries requires only a small part of the energies of the community, all the rest being set free for the production of either leisure or luxuries, including, among luxuries, education, science, literature, art, and warfare. Thus man is rendered freer by industrialism, since his bondage to Nature is diminished; but each separate man may not be freer, since there is an increase in the pressure of the community upon the individual.

By diminishing man's bondage to Nature, industrialism has rendered physically possible many things

of great value which were only partially possible in earlier stages. The mere business of keeping alive is shared by man with the lower animals, and does not raise him above their level in any important respect. What raises him above the level of the animals is his mental capacity, which has brought with it desires that are not merely material. When men are liberated from the pressure of the struggle to obtain food, they do not all sink into sloth and idleness; some remain active, but in the pursuit of knowledge or art or some other purely mental object. It is the work of these men that sheds luster on mankind as a whole. To have lived a certain number of years, consumed a certain amount of food, begotten a certain number of children similar to oneself, and then died, is not the utmost of which men are capable; yet, owing to the scant productivity of labor, it was, until lately, all that most men could hope to achieve. Now, so far as physical conditions are concerned, better possibilities exist; education and sufficient leisure could, if we chose, exist throughout the whole community, and the business of keeping alive could become an easy and unimportant part of our daily occupation.

What is called civilization may be defined as the pursuit of objects not biologically necessary for survival. It first arose through the introduction of agriculture in the fertile deltas of great rivers, more particularly in Egypt and Babylonia. Everywhere else primitive agriculture exhausts the soil and compels frequent migrations, but this was not the case in

the deltas. Here the surplus food produced by one man's needs was sufficient to make possible the creation of a small leisure class, and it was this small leisure class that invented writing, architecture, mathematics, astronomy, and other arts essential to all subsequent civilization. Although the class that could share in civilized pursuits increased with the improvement of agriculture and the growth of commerce, it remained unavoidably small, because labor was still not sufficiently productive to create the necessaries of life except by the whole work of most of the community. Now, though the arts and sciences remain a prerogative of the few, there is no good reason why this should be the case; it would be possible for every man and woman to have as great a share of them as he or she might desire. If every man and woman worked for four hours a day at necessary work, we could all have enough; and the leisure remaining after four hours' work is amply sufficient for even the most intensive cultivation of science or art. This fact has destroyed the only strong argument that ever existed for an oligarchic organization of society, whether economic or political, and has made it almost inevitable that, if industrialism continues without disaster, its ultimate form must be socialism, which alone avoids inequalities for which the former reason no longer exists.

The desire to diffuse civilization has, it is true, played only a very small part hitherto in the development of industrialism, and it is perhaps hardly to be hoped that it will play a great part until after

the establishment of socialism. There has, however, been a very considerable diffusion of civilization in industrial countries, owing to the operation of motives that were mainly economic. A man who has some education is a more efficient worker than one who can neither read nor write; hence all industrial countries have adopted universal compulsory education. This would scarcely have been possible without industrialism, since the time of teachers and pupils could not easily have been spared from more immediately necessary work. With the coming of industrialism and the complicated processes that it introduces, universal education becomes both more possible and more obviously necessary; increase of education may therefore be taken as one of the inherent tendencies of industrialism.

With universal education come other things of great importance. The first of these is political democracy, which is scarcely possible where the working class is uneducated, and scarcely avoidable where it is educated. By democracy, I do not necessarily mean a parliamentary régime; the soviet system, as originally conceived, would have been quite compatible with democracy. What I mean by democracy is a system under which all ordinary men and women participate equally in fundamental political power, though exceptional people may be excluded for special reasons, such as endeavoring to upset by force the government desired by the majority. Interpreted in this wide sense, political democracy seems to be the system of government natural to an ad-

vanced industrial community, except in times of special stress, such as revolution or war.

Industrialism, as we have seen, diminishes the freedom of the individual in relation to the community, but increases the freedom of the community in relation to Nature. That is to say, the actions of the individual, at any rate, in the economic part of his life, become increasingly controlled by the actions of the community, or by some large organization such as a trust; but the actions of the community become less and less controlled by the primitive necessity of keeping alive. Hence individual passions, such as those which produce art and romance, tend to die out, while collective passions, such as those which produce war, sanitation, and elementary education, are liberated and strengthened. Each of these deserves separate consideration.

The decay of individual passion brings with it, first of all, a diminution of individuality. In a thoroughly industrialized community, such as the United States, there is little appreciable difference between one person and another; eccentricity is hated, and every man and woman endeavors to be as like his or her neighbors as possible. Their clothes, their houses, their household utensils, are all produced to standard pattern by the million, without any of those individual differences that characterize the products of handicrafts. And it seems that the men and women wish to assimilate themselves to the articles they use by forcing upon themselves the sameness of manufactured articles, as though the Creator

himself had adopted industrial methods and were producing men and women wholesale with the very latest machinery warranted to make each specimen up to sample.

In such an atmosphere, art and romance and individual affection cannot flourish, since they involve preservation of individuality in oneself and recognition of it in others. There are other reasons, also, why such things decay under industrialism as it has been practiced hitherto, but there is one point connected with the decay of romance that belongs to our present topic. The instinct for romance when it is denied an outlet in one's own life, seeks, as instincts will, a vicarious satisfaction in imagination. Hence the passion for sensational stories, melodramas, and murder cases. A lunatic who kills his wife with every circumstance of horror is a public benefactor: into a thousand tame and listless lives he introduces the imaginative satisfaction of fierce passion. Every detail in the newspapers is eagerly devoured by men who dare not, in their own conduct, depart a hair's breadth from respectable rectitude, for fear of losing their jobs. At the outbreak of war the delights of many of those who expect to be noncombatants has the same source; the gladiatorial show relieves the deadly monotony of the office or the factory even better than a football match or a horse-race. And in spite of all knowledge to the contrary, noncombatants persist in imagining modern war on the Homeric pattern, as an affair of individual bravery and initiative; for the dreary mechanistic mass

action that constitutes the actual operations affords no outlet to the starved instinct for individual romance. This same boredom and desire for excitement does much to increase the fierceness of revolutionary movements and to produce the preference for revolution as against more gradual and less sensational methods. . . .

Religion, in its traditional form, appears to be difficult to combine with industrialism, although it is by no means obvious why this should be the case. Of course, the successful capitalists remain religious, partly because they have every reason to thank God for their blessings, and partly because religion is a conservative force, tending to repress the rebelliousness of wage-earners. But industrial wage-earners everywhere tend to lose their religious beliefs. I think this is partly for the merely accidental reason that the teachers of religion derive their incomes either from endowments or from the bounty of the rich, and therefore often take the side of the rich and represent religion itself as being on this side. But this cannot be the sole reason, since, if it were, wage-earners would invent democratic variants of the traditional religion, as was done by the English independents in the seventeenth century and by the peasants who revolted against agrarian oppression in the Middle Ages and in the time of Luther. It is singularly easy to adapt Christianity to the needs of the poor, since it is only necessary to revert to the teachings of Christ. Yet that is not the course that industrial populations take; on the contrary, they

tend everywhere to atheism and materialism. Their rebellion against traditional religion must, therefore, have some deeper cause than the mere accidents of present-day politics.

The chief reason is, I believe, that the welfare of industrial wage-earners is more dependent upon human agency and less upon natural causes than is the case with people whose manner of life is more primitive. People who depend upon the weather are always apt to be religious, because the weather is capricious and non-human and is therefore regarded as of divine origin. On the rockbound coast of Brittany, where Atlantic storms make seafaring a constant and imminent peril, the fishermen are more religious than any other population of Europe: churches crowd the coast, particularly its most dangerous portions, while every headland has its Calvary, with the lofty crucifix so placed as to be visible many miles out to sea. While the fisherman is at sea, he and his wife pray for his safe return; as soon as he lands, his relief finds expression in drunkenness. A life of this kind, exposed constantly to non-human dangers, is the most favorable to traditional religion. Indeed, the whole of traditional religion may be regarded as an attempt to mitigate the terror inspired by destructive natural forces. Sir J. G. Frazer, in his *Golden Bough,* has shown that most of the elements in Christianity are derived from worship of the spirit of vegetation, the religion invented in the infancy of agriculture to insure the fertility of the soil. Harvest Thanksgiving, prayers for rain or

fair weather, and so on, illustrate what has been really vital in religion. To the peasant, fertility and famine are sent by God and religious rites exist to secure the one and avert the other.

The industrial worker is not dependent upon the weather or the seasons, except in a very minor degree. The causes which make his prosperity or misfortune seem to him, in the main, to be purely human and easily ascertainable. It is true that natural causes affect him, but they are not such as we are accustomed to attribute to supernatural agency. God may send rain in answer to prayer, because the need of rain was felt while religion was still young and creative. But although a population may be ruined by the exhaustion of its coal fields, no one supposes that God would create new seams however earnestly the miners were to pray. Petroleum may bring prosperity, but if Moses had brought petroleum out of the rock instead of water, we should have regarded the occurrence as a fact of geology, not as a miracle. The fact is that religion is no longer sufficiently vital to take hold of anything new; it was formed long ago to suit certain ancient needs, and has subsisted by the force of tradition, but is no longer able to assimilate anything that cannot be viewed traditionally. Hence the alteration of daily habits and interests resulting from industrialism has proved fatal to the religious outlook, which has grown dim even among those who have not explicitly rejected it. This is, I believe, the fundamental reason for the decay of religion in modern communities.

The lessened vitality of religion, which has made it unable to survive new conditions, is in the main attributable to science.

There is one other tendency which has hitherto been very strong in industrialism, but which, I believe, might cease to characterize industry under socialism; I mean the tendency to value things for their uses rather than for their intrinsic worth. The essence of industrialism, as we saw, is an extension of the practice of making tools. In an industrial community the great majority of the population are not making consumable commodities, but only machines and appliances by means of which others can make consumable commodities. This leads men to become utilitarian rather than artistic, since their product has not in itself any direct human value. The man who makes a railway is regarded as more important than the man who visits his friends by traveling on it, although the purpose of the railway is to be traveled on. The man who reads a book is thought to be wasting his time, whereas the man who makes the paper, the man who sets the type, the man who does the binding, and the librarian who catalogues it are all regarded as performing valuable functions. The journey from means to end is so long, and the distinctive merits of industrialism are so exclusively concerned with means, that people lose sight of the end altogether and come to think more production the only thing that is of importance. Quantity is valued more than quality, and mechanism more than its uses.

This reason, as well as the one previously mentioned, accounts for the decay of art and romance under industrialism. But the utilitarian tendency of industrialized thought goes deeper than the decay of art and romance; it upsets men's dreams of a better world, and their whole conception of the springs of action. It has come to be thought that the important part of a man's life is the economic part, because this is the part concerned with production and utilities. It is true that, at present, the economic part needs our thought, because it is diseased; just as, when a man's leg is broken, it is temporarily the most important part of his body. But when it is healed and he can walk on it, he forgets about it. So it ought to be with the economic part of life; we ought to be able to use it without having to think of it all day long. The bodily needs of all could be supplied as a matter of course by means of a few hours of daily labor on the part of every man and woman in the community. But it should be the remaining hours that would be regarded as important,—hours that could be devoted to enjoyment of art or study, to affection and woodlands and sunshine in green fields. The mechanistic utopian is unable to value these things: he sees in his dreams a world where goods are produced more and more easily and are distributed with impartial justice to workers too tired and bored to know how to enjoy them. What men are to do with leisure he neither knows nor cares; presumably they are to sleep till the time for work comes round again.

This utilitarianizing of men's outlook is, I believe,

not inseparable from industrialism, but due to the fact that its growth has been dominated by commercialism and competition. A socialistic industry could be the servant, not the master, of the community; this is one fundamental reason for preferring socialism to capitalism. I wish to warn the advocates of economic reconstruction against the danger of adopting the vices of their opponents by regarding man as a tool for producing goods rather than goods as a subordinate necessity for liberating the non-material side of human life. Man's true life does not consist in the business of filling his belly and clothing his body, but in art and thought and love, in the creation and contemplation of beauty, and in the scientific understanding of the world. If the world is to be regenerated, it is in these things, not only in material goods, that all must be enabled to participate.